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Factors affecting the biomass pellet using industrial eucalyptus bark residue

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Abstract

Eucalyptus is utilized in the timber and paper industries. The eucalyptus bark must be peeled off during the production process, which results in a large amount of biomass residue. The objectives of this research were (i) to study the physical properties of eucalyptus bark, (ii) to investigate the crushing process using a hammer mill, and (iii) to examine the pelletizing factors of biofuel from eucalyptus bark residue using a pellet machine. Eucalyptus bark was crushed to reduce particle size and then sieved through different screen sizes (3, 4, and 5 mm) at a drum speed of 1200 rpm. The resulting eucalyptus powder was used to study the pelletizing factors of biofuel at various levels of moisture content: 17.69, 20.21, 24.27, and 26.74% w.b. and various pelletizing speeds of 250, 275, and 300 rpm. It was found that the eucalyptus powder could be pelletized at a speed of 275 rpm. Pellets with screen sizes of 3 and 4 mm could be pelletized at a moisture content of 17.69% w.b., while a screen size of 5 mm could be sued to pelletize at a moisture content of 20.21% w.b. The specific energy consumption from the particle size reduction process to the pelletizing process ranged from 667.92 to 854.64 kJ/kg. The results of bulk density, durability, and fines were 603.20–645.73 kg/m³, 96.34–96.88%, and 1.83–2.02%, respectively. The heating value was 16.19 MJ/kg. The energy value was calculated by using a eucalyptus pellet as boiler fuel (at a boiler efficiency of 38%). Eucalyptus pellets have the potential to produce energy worth 644 million THB/year or 20.6 million USD/year.

Keywords Eucalyptus · Pellets · Biomass · Palletizing

1 Introduction

The increasing energy demand around the world is a result of technological developments. Many countries are concerned about the sustainability and environmental impact of using fossil fuels [1]. Global energy consumption is expected to increase by 2.2% in 2022 due to the economy recovering from the pandemic crisis. Compared to the previous years of the Covid-19 pandemic, all types of energy, except nuclear power, will benefit from the increase in energy demand, which will drive energy prices higher [2].

Renewable energy obtained from natural sources can be defined as "energy obtained from continuous or repetitive currents recurring in the natural environment" [3]. Renewable energy sources cover the full spectrum of renewable energy technologies and are utilized around the world. Renewable energy resources (e.g., biofuels, solar thermal, solar cell, wind power, hydropower, waves, tidal, geothermal, and ocean-thermal) are important factors for the energy strategy of every country [4]. As the world develops, fossil fuels are rapidly being depleted due to the increase in

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energy demand. Therefore, biofuels are needed to replace the use of fossil fuels [5, 6]. The demand for biofuels and renewable energy (including biofuels but excluding hydropower) has increased by 3.4% and 9.7%, respectively, similar to the increase in demand in the years 2017, 2018, and 2019 [7]. However, the idea of using renewable energy has to be carefully established, especially in the case of biomass [8]. Biomass is an organic compound obtained from plant photosynthesis processes by using carbon dioxide (CO_2) and water [9]. The byproduct of biomass residue obtained from the industrial and agricultural processes is a potential renewable energy source [10]. It is particularly attractive for heat energy production as well as for reducing carbon dioxide (CO_2) emissions. Biomass materials such as wood, sawdust, straw, and paper waste [11] are utilized for various energy needs, including electricity production and heat energy in industrial plants [12, 13]. The commonly utilized biomass consists of (1) wood and agricultural products, (2) solid waste, (3) landfill gas, and (4) alcohol fuels [14, 15].

Biomass pellets are the conversion of biomass materials into a standard form of fuel (e.g., En-Plus, Din-Plus) for easy transport and use. There are various types of biomass material used in the production of biomass pellets. The quality of biomass pellets depends on the properties of the raw materials and production process [16–18], which will affect the physicochemical properties of the final product, such as cellulose and lignin content. Lignin promotes the binding ability of biomass pellets and is a factor in the compression process. The production of biomass pellets consists of several processes including material preparation and post-pelletizing (Fig. 1). Effective storage of the materials is necessary to prevent impurities in biomass. Rain and moisture can damage the raw materials as well [17].

Most of the industrial biomass residue is large, so a particle reduction process is necessary (preparing raw materials). The unusable material (stones or metal scrap) should be removed from the raw material before the crushing process [20, 21] because stones and metals can damage the mechanical equipment (i.e., the hammer mill and pellet press). The material crushing process must reduce the particle size evenly. The crushed material must be smaller than the die hole to prevent clogging. Therefore, the material size should be smaller than the die diameter [22]. The size of material suitable for pelletizing process is under 5 mm in diameter. However, excess amounts of material smaller than 0.5 mm will affect the friction and pellet quality [23]. The optimum moisture content of the material should be between 10 and 20% to ensure the quality of biomass pellets. In the case of the improper moisture content of materials, a drying process is required [16]. Excess moisture causes low combustion temperatures, low energy efficiency, and high emissions of hydrocarbon and particulate [24]. However, some materials are not suitable for pelletizing. They need to be mixed with other materials to increase the yield of
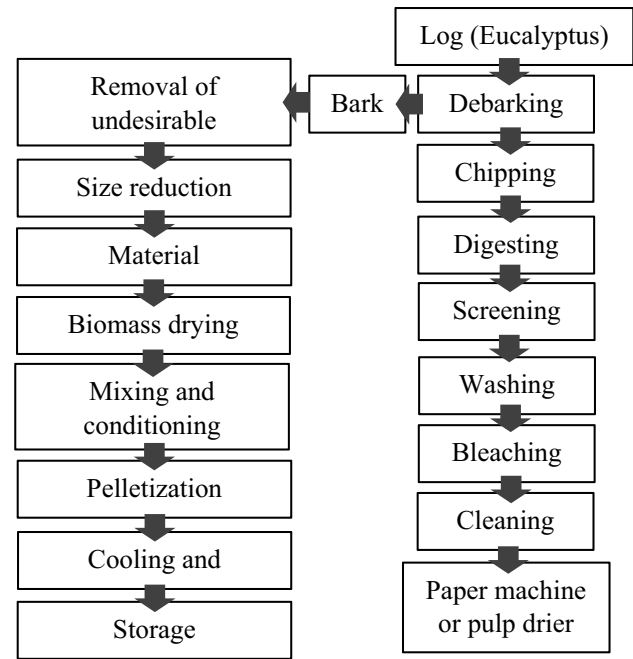

Fig. 1 Stages of the pelletization process as well as pulp and paper-making processes [16, 19]

biomass pellets and improve the final properties of the biomass pellets [16]. The pelletizing process requires pressure to press materials through the die hole. The pellet machine has two main components, comprising a die plate with holes and rollers that force the material through the die holes. The increasing pressure and friction cause an increase in temperature as well, which softens the lignin and fibers, transforming them into pellets [25, 26]. At the same time, the moisture content decreases due to the increase in temperature. The biomass pellets have a size of 6–8 mm in diameter and 3.15–45 mm in length. Biomass pellets that are longer than 40 mm in length must not exceed 1% [27]. The biomass pellets with moisture content higher than 20% d.b. could cause bacterial growth [28, 29], and lead to material deterioration. The post-pelletizing process should concern the moisture content of the material before beginning the storage or packaging process.

The pulp and paper industries transform biomass materials that contain lignocellulosic into paper products [30]. Eucalyptus is an important raw material for pulp production. Because it cannot be used in paper production, eucalyptus wood is peeled from logs during the papermaking process (debarking). It is then chipped before being digested, where chemicals and heat dissolve the lignin while leaving the undissolved pulp. Following the completion of the pulp preparation process, it will be screened to remove foreign matter from the membrane. After sorting, it is washed to remove the pulping liquid (such as chemicals, lignin, and other liquid fiber components known as black liquor) and sent to storage tanks before bleaching in order to improve whiteness quality. Before beginning the paper

manufacturing process, the bleached pulp must be cleaned to remove contaminants [19]. After the production process, there is 18–20% of waste eucalyptus bark [31, 32]. Figure 1 depicts the relationship between the biomass pelleting process and the paper production process. Eucalyptus bark can be utilized for chromium absorption in effluents to reduce the pH of effluents [33, 34]. The independent rapid pyrolysis of eucalyptus bark at temperatures ranging from 400 to 550 °C can produce bio-oil, char, and gas. Additionally, mixing bio-oil with alcohol (2.5–10%) can improve viscosity, stability, and heating value [35, 36]. The mixing of 20–40% eucalyptus bark with lignite can reduce the emissions of CO_2, NO_2, and SO_2 [37]. The eucalyptus bark can be used to produce energy as well [38].

In 2018, the eucalyptus cultivation areas in Thailand totaled 107,000 rai. The average yield was 8–12 t per rai, representing 0.86–1.28 million tons. The eucalyptus bark residue from the production process was 20%, representing 0.17–0.26 million tons [39]. Most eucalyptus bark is dumped and unused, which creates a risk for fire due to the high internal temperature of the dumped piles. Only 0.5 million tons of eucalyptus bark are utilized as biofuel in the power or heating industry, due to the high moisture content of eucalyptus bark. Moreover, eucalyptus bark has a light weight, which causes high costs for transportation. The uneven size of materials affects the fuel feed system of boilers. Industrial plants demand eucalyptus bark as biofuel. Prapakarn et al. [40] studied the properties of eucalyptus bark pellets, consisting of the heating value (17.78 MJ/kg), moisture content (11.90%), and durability (93.25%). As previously stated, pelletizing is an important process that produces high-quality products. However, the appropriate pelletizing factors have not been studied because each type of biomass has different physical properties. As a result, it is necessary to investigate the factors influencing the quality and pelletizing process of eucalyptus bark, using eucalyptus bark residue from the industry to produce biomass pellets. The suitable factors for pelletizing biofuel from eucalyptus bark should be determined. The results could be used as the foundation for machine design and the proper operation of related machines. Furthermore, the results could be used to improve and develop existing machines with the goal of producing higher-quality biomass pellets. This research promoted the source of raw materials for fuel in biomass power plants and the utilization of agricultural residue.

2 Experimental

2.1 Material preparation

The material in this study was eucalyptus bark residue from a paper factory in Khon Kaen Province, Thailand (16°41′52.85″ N 102°45′13.48″ E). The factory used eucalyptus stems with a diameter of at least 3.81 cm, which were cut into logs with a length from 1.8 to 2.2 m. The bark was then removed to eliminate the impurities and low fiber. The composition of the eucalyptus bark was studied at the Agricultural Machinery Research Center Laboratory and Postharvest Science Agricultural Engineering, Faculty of Engineering, Khon Kaen University. The initial moisture content of eucalyptus bark was 59.05% w.b. The bark was stored to reduce the moisture content to less than 30% w.b. Subsequently, a sample of 500 g was drawn at random and sieved through a 3.17-mm (1/8 in) screen. The components were separated into small pieces of bark, bark, and wood. Before crushing, the eucalyptus bark was air-dried to reduce the moisture content to less than 30% w.b. The eucalyptus bark was then reduced in size using a hammer mill, which consists of 42 swinging hammers attached to a shaft driven by a 5-hp electric motor. The sieve's screen sizes were 3, 4, and 5 mm using a drum speed of 1200 rpm [21]. The crushed samples (Fig. 2a–c) were studied for the physical and thermal properties of eucalyptus bark powder, consisting of moisture content, average particle size, static friction coefficient, angle of repose, bulk density, proximate analysis, ultimate analysis, and thermal properties, as shown in Table 1.

2.2 Study of the factors affecting the biomass pelletizing process for eucalyptus bark

The machine had a rotary disc compressor with a diameter of 26 cm and a die hole had a diameter of 6 mm. The machine's motor had power rated at 7.5 hp (Fig. 3). The motor speed was adjustable. Crushed eucalyptus powder was sieved through 3 different screen sizes, after which it was varied for different levels of moisture content at 17.69, 20.21, 24.27, and 26.74% w.b. The eucalyptus powder was pelletized at 3 die speeds of 250, 275, and 300 rpm (3.40, 3.74, and 4.08 m/s, respectively). The optimum conditions for the biomass pellet machine and biomass properties of the biomass pellets were investigated. Three samples of biomass pellets were randomly sampled. The operation time of the machine was recorded, including specific energy consumption. The biomass pellets were weighed. Data were recorded for each replicate of the pelletizing process. The specific energy consumption (SEC) (Eq. 1) was calculated for pelletizing. The biomass pellets were then air-dried for 72 h to keep the moisture content below 10% wb, as required by the ENplus standard [27], before being investigated for eucalyptus bark properties.

$$SEC = \frac{Energy used}{Product's amount} \tag{1}$$

2.2.1 Data analysis

The results were analyzed statistically using the $3 \times 4 \times 3$ factorial experiment in completely randomized design (CRD).

Fig. 2 Eucalyptus powder after being crushed with a hammer mill (**a**–**c**) and samples of eucalyptus pellets (**d**–**f**)

(a) screen size 3 mm

(b) screen size 4 mm

(c) screen size 5 mm

(d) screen size 3 mm
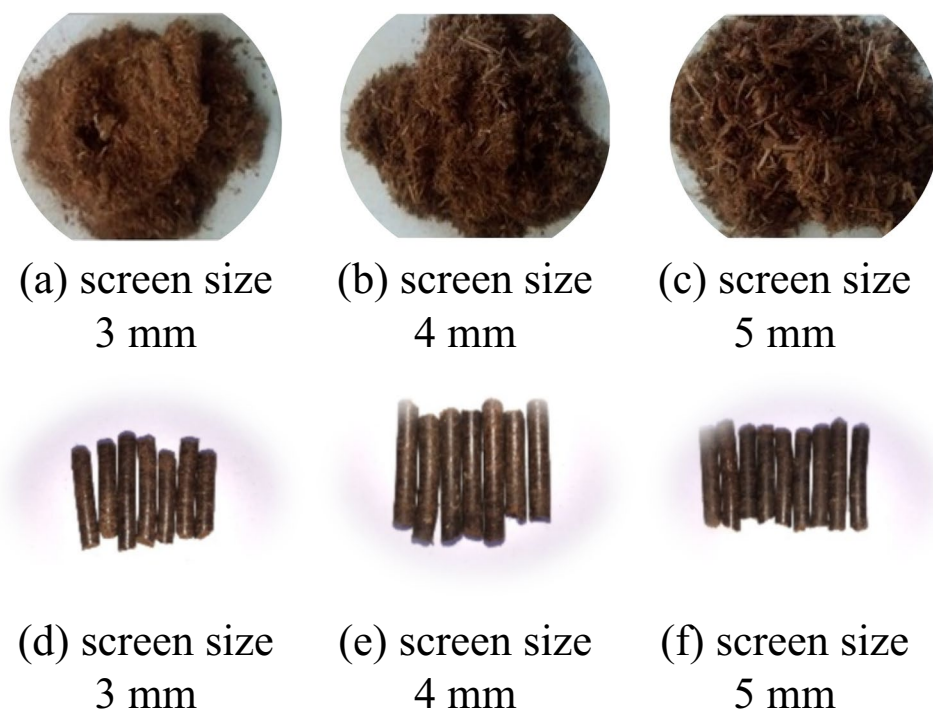
(e) screen size 4 mm

(f) screen size 5 mm

Table 1 Physical properties of eucalyptus bark, eucalyptus powder, proximate analysis, and ultimate analysis

| Properties	Eucalyptus bark [21]	Eucalyptus powder		
		Screen size 3 mm	Screen size 4 mm	Screen size 5 mm
Physical properties				
Moisture content (% w.b.)	10.50	24.64	25.88	25.91
Bulk density (kg/m³)	651.04	243.38	223.70	222.02
Coefficient of static friction on various surfaces				
Mild steel	0.55	0.58	0.57	0.63
Plywood	0.60	0.59	0.61	0.60
Rubber	0.65	0.51	0.51	0.56
Zinc	0.52	0.56	0.62	0.67
Angle of repose (°)	61.8	57.63	59.96	60.78
Particle size (mm)	N/A	0.58	0.99	1.03
		Biomass pellet standards ENplus Handbook [27]		
		ENplus A1	ENplus A2	ENplus B
Proximate analysis				
Moisture contents (%)	10.50	≤ 10	≤ 10	≤ 10
Volatile material (%)	69.50	N/A	N/A	N/A
Fixed carbon (%)	11.03	N/A	N/A	N/A
Ashes (%)	8.97	≤ 0.7	≤ 1.2	≤ 2.0
Ultimate analysis				
Carbon (%)	38.10	N/A	N/A	N/A
Hydrogen (%)	6.11	N/A	N/A	N/A
Nitrogen (%)	0.25	≤ 0.3	≤ 0.5	≤ 1.0
Oxygen (%)	44.18	N/A	N/A	N/A
Sulfur (%)	N/A	≤ 0.04	≤ 0.05	≤ 0.05
Chlorine (%)	0.04	≤ 0.02	≤ 0.03	≤ 0.03
Heating value (kcal/kg)	3625.37			

N/A not available
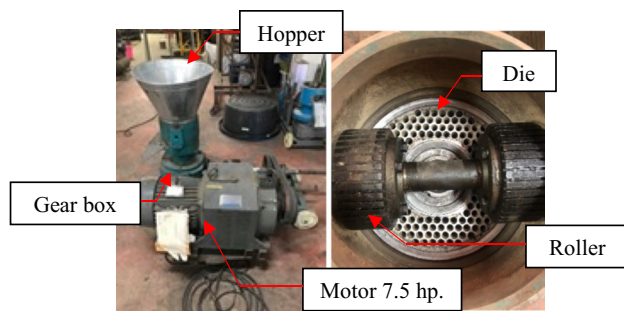
Fig. 3 Flat die pelleting machine

The variance was analyzed according to the experiment. The mean was compared using the least significant difference (LSD) at a 95% confidence level [41, 42]. The interaction between factors was analyzed to explore the suitable moisture content and speed of the compression plate.

2.3 Property analysis of the biomass pellets obtained from the experiment

The following properties of biomass pellets were determined using eucalyptus after the pelleting process (Fig. 2d–f).

2.3.1 Physical property analysis

Bulk density Biomass pellets were released into a container. A smooth surface material was used to scrape the excess pellets out of the container. Then, the pellets in the container were weighed as the weight of biomass pellet per packing volume of 1000 cm^3 [43, 44].

Diameter and length Biomass pellets were randomly sampled and measured for diameter and length. A 0.05-mm Vernier caliper was used. Diameters were recorded at 6.35–7.25 mm or 0.250–0.285 in, according to the Pellet Fuel Institute (PFI) Standard (Sect. 6.1.2). Pellets that were longer than 38.1 mm or 1.5 in were recorded. Pellets longer than 38.1 mm should be less than 1%, according to the PFI Standard (Sect. 6.1.7).

Durability Five hundred grams of biomass pellets were tested for durability. The machine was turned on, and the rotation speed of the machine was set at 50 rpm. The test was performed for 10 min, after which the pellets were sieved through a 3.17-mm (1/8 in) screen size to remove powder and breakage from becoming tested following ASTM standards (E1288-89). Pellets remaining on the screen were weighed and calculated for durability using Eq. 2 [45, 46].

$$PDI = \frac{WPW}{IW} \times 100 \tag{2}$$

where PDI = durability of biomass pellet, WPW = weight of unbreakable biomass pellet (g), and IW = initial weight of biomass pellets (g).

Fines One thousand one hundred thirty-three grams of biomass pellets (2.5 pounds) was sampled and recorded as the initial weight. A sieve with a screen size of 3.17 mm (1/8 in) was used and attached to the receiving tray. The biomass pellets were loaded on the sieve. The maximum load of pellets on the sieve should not exceed 453 g (1 pound) per 654 cm^2 (100 in^2) of sieve surface area. Biomass pellets were sorted by shaking the sieve to the side 10 times. The process was repeated until all pellet samples were sorted. The weight of the receiving tray was weighed and recorded. The recorded data were calculated using Eq. 3 [47, 48].

$$\%F = \frac{\left[(W_p + F) - W_p\right]}{W_i} \times 100 \tag{3}$$

where %F = fines (%), W_p = weight of fines receiving tray (g), and W_i = initial weight of biomass pellets (g).

2.3.2 Heating value

The heating value was determined according to the ASTM standard (E 711–87). Pellet samples were tested for heating value using a Bomb calorimeter (Brand Art.2060/2070). Samples of biomass pellets were weighed and recorded. Wire and thread 6 cm long were used and weighed. Wire (nickel–chromium has a calorific value of 0.269896 cal per gram) was connected between two electrodes, after which the thread was tied with the pellet sample and connected with the wire. The cover of the bomb body was completely closed. Oxygen and water were used to fill the 2000-mL calorimeter tank. The bomb body was connected with a power cable and put in the calorimeter tank. The machine was turned on for 5 min until the temperature stabilized. The temperature was recorded every 1 min. Then, the ignition switch was pressed to ignite the pellet. Time and temperature from the thermometer were recorded from the beginning of ignition until the temperature was stable. After that, the machine was turned off and the bomb body was removed from the calorimeter tank. Air was released, and the cover of the bomb body was opened. The remaining wire was measured for length to calculate the burned length. Data were used to calculate the heating values, according to Eqs. 4 and 5, where C_b = 26,441.6 J/g, W_b = 1.6215 g, C_w = 1401.64 J/g, C_c = 17,482.12 J/g, and N_c = 25.02 J/g.

This is the result of calibration with dry benzoic acid (which has a constant heat value).

$$H = \frac{\left(C_b \times W_b\right) + C_w + C_c + N_n}{\triangle T} \qquad (4)$$

$$C_v = \frac{\left(H \times \triangle T\right) - C_w - C_c}{W_s} \qquad (5)$$

where H = heat capacity (J/°C), C_b = heating value of benzoic acid (J/g), W_b = weight of benzoic acid (g), C_w = heating value of firing wire (J/g), C_c = heating value of firing cotton (J/g), N_c = heating value of nitrogen (J/g), C_v = heating value of sample (J/g), W_s = sample weight (g), C_c = heating value of firing cotton (J/g), C_w = heating value of firing wire (J/g), and ΔT = changing temperature (°C).

2.3.3 Energy density

This indicates the energy density of improved physical and chemical properties of commercial biomass. The energy density is the energy that can be stored in a mass or system [49, 50]. It can be calculated according to Eq. 6.

Energy density = (heating value) × (bulk density) (6)

where energy density (MJ/m^3), heating value (MJ), and bulk density (kg/m3).

2.4 Economic analysis

Economic analysis was evaluated to determine the possibility of using eucalyptus bark as fuel. A cost analysis of pellet production was performed by calculating the value of electricity generated from the thermal conductivity of eucalyptus pellets in a biomass boiler, at a boiler efficiency of 38% [51].

3 Results and discussion

The eucalyptus powder of each screen size, rotation speed, and moisture content resulted in significantly different specific energy, fines, bulk density, and durability, at a 99% confidence level. However, the eucalyptus powder had no significant effect on heating values. The interaction between the eucalyptus powder and rotation speed resulted in statistically different specific energy (at a 95% confidence level) and bulk density (at a 99% confidence level). The interaction between the eucalyptus bark powder and rotation speed had no significant effect on durability, fines, or heating value. The interaction between the eucalyptus bark powder and moisture content had no significant effect on specific energy, bulk density, durability, fines, or heating value. The interaction between rotation speed and moisture content resulted in statistically different specific energy (at 95% confidence level) but had no significant effect on bulk density, durability, fines, or heating value. The interaction between the three parameters had no statistical effect on specific energy, bulk density, durability, fines, or heating value (Table 2). The coefficient of variation (CV %) of specific energy, bulk density, durability, and fine and heating value were 7.87, 4.70, 0.89, 12.34, and 4.64%, respectively. In general, the coefficient of variation should not be greater than 10% [52]. According to Kaliyan and Morey [53], the factors that increase pellet durability result in increased density, although there is no known relationship between durability and biomass pellet density. Increased humidity also results in a decrease in the

Table 2 Statistical analysis of eucalyptus bark powder, die speed, and moisture content affecting various indicators

Source	df	F value				
		SEC	Bulk density	Durability	Fine	Heating value
Screen size (A)	2	50.50**	43.17**	5.59**	12.09**	0.83 ns
Die speed (B)	2	13.08**	31.42**	10.94**	8.96**	0.62 ns
Moisture content (C)	3	29.61**	131.16**	101.86**	719.65**	1.58 ns
AB	4	3.05*	4.37**	0.51 ns	0.08 ns	0.31 ns
AC	6	1.05 ns	0.93 ns	1.56 ns	0.59 ns	0.93 ns
BC	6	2.40*	0.24 ns	0.44 ns	0.52 ns	1.02 ns
ABC	12	0.89 ns	0.64 ns	0.39 ns	0.12 ns	0.83 ns
Error	70					
Total	107					
CV (%)		7.87	4.70	0.89	12.34	4.64

ns non-significant

**Highly significant at 1% level

*Significant at 5% level

bulk density of biomass pellets since the pellets increase in volume as they absorb more moisture [54].

3.1 Specific energy consumption (SEC) of pelletizing

Tables 2 and 3 show the comparison of die speed, screen size, and moisture content affecting the specific energy. The eucalyptus powder at different die speeds, screen sizes, and moisture content resulted in statistically different specific energy consumption. Figure 4a shows the decline of specific energy consumption when moisture content increased from 17.69 to 20.21% w.b. But the specific energy consumption increased when moisture content increased from 20.21 to 26.74% w.b. The SO/DS 4:275 and 4:300 decreased as the moisture content increased from 24.27 to 26.74% w.b. The SO/DS 3:275 had the lowest specific energy consumption, 597.78 kJ/kg, at a moisture content of 20.21% w.b., followed by SO/DS 3:300, at 632.02 kJ/kg and moisture content of 20.21% w.b. The third rank was SO/DS 4:275, at a specific energy consumption of 677.92 kJ/kg, moisture content of 20.21% w.b. While the top three highest specific energy consumption were SO/DS 4:250 at a moisture content of 26.74% w.b. (910.37 kJ/kg), followed by SO/DS 5:250 at a moisture content of 17.69% w.b. (897.80 kJ/kg), and SO/DS 4:250 at a moisture content of 24.27% w.b. (864.87 kJ/kg). The results showed that the moisture content of 20.21% w.b. had the lowest specific energy consumption because the

water content in the material reduced friction in the die and resulted in low SEC [55]. On the other hand, lower moisture content caused higher friction between material and die, which resulted in higher specific energy consumption [56]. In general (Fig. 5), the SEC during pelletizing is affected by the moisture content of the material, die dimensions, material composition, feeding rate, and die speed [57].

The specific energy analysis throughout the production of eucalyptus bark pellet fuel was obtained by adding the specific energy in the eucalyptus bark reduction study of Sanchumpu et al. [21] (Fig. 6) and the specific energy of the pellet study results (Fig. 4a) using certain biomass pellet standards as indicators (density, durability, and fine). When the total specific energy consumption was calculated, it was discovered that in the eucalyptus bark reduction process for all three screen sizes, the optimum hammer mill drum speed was 1200 rpm, and the moisture content ranged from 17.64 to 20.21% w.b. The lowest specific energy consumption was found with a screen size of 4 mm, a moisture content of 20.21% w.b., followed by 3 mm at 20.12% w.b., and 3 mm at 17.69% w.b., with a total specific energy of 737.64, 769.46, and 827.89 kJ/kg, respectively, as shown in Fig. 6. The results of SEC could be used for energy consumption analysis and development of the production process of eucalyptus pellets.

3.2 Density

Tables 2 and 3 show the comparison of die speed, screen size, and moisture content affecting the bulk density of biomass pellets. The eucalyptus powder at different die speeds, screen sizes, and moisture content resulted in different bulk densities. From Fig. 4b, as the initial moisture content of the material increased, the bulk density tended to decrease for each factor. The SO/DS of 3:275, 3:250, and 3:300 had the top three highest bulk densities at 645.73, 642.13, and 629.03 kg/m³, respectively. The moisture content and powder particles caused the mixed material to loosely compress. High moisture content during the palletizing process will cause porosity in the pellets after they reduce moisture content, leading to the reduction of pellet density [55]. The bulk density of pellets is an important quality indicator for the evaluation of storage, space, and distribution systems, including the efficiency of transportation, management, and storage. High bulk density leads to the high efficiency of transportation and can reduce storage space [58]. The bulk density of pellets should be between 600 and 650 kg/m³ [27]. In this study, the initial moisture content of 17.69% w.b. at SO/DS 3:250, 3:275, 3:300, 4:250, 4:275, and 5:275 and the initial moisture content of 20.21% w.b. at SO/DS 3:250 and 3:275 had a bulk density that conformed to the standard.

Table 3 Die speed, screen size, and moisture content affecting the average specific energy, average bulk density, average durability, and average fines

	Specific energy (kJ/kg)	Bulk density (kg/m³)	Durability (%)	Fines (%)
Die speed (rpm)				
250	819.00b	546.86a	95.99a	3.78a
275	731.41a	557.62a	95.50ab	3.93ab
300	788.50ab	506.66b	95.00b	4.25b
LSD$_{0.05}$	57.28	23.81	0.80	0.46
Screen size (mm)				
3	711.83a	570.85a	95.89a	3.73a
4	806.69b	520.68b	95.41a	3.95ab
5	803.77b	525.31b	95.24a	4.30b
LSD$_{0.05}$	57.28	23.81	0.80	0.46
Moisture content (% w.b.)				
17.69	817.31b	604.95a	97.13a	1.71a
20.21	695.05a	559.85b	96.56a	2.15b
24.27	782017b	517.37c	94.89b	4.98c
26.74	801.90b	473.61d	93.47c	7.13d
LSD$_{0.05}$	49.61	20.62	0.70	0.40

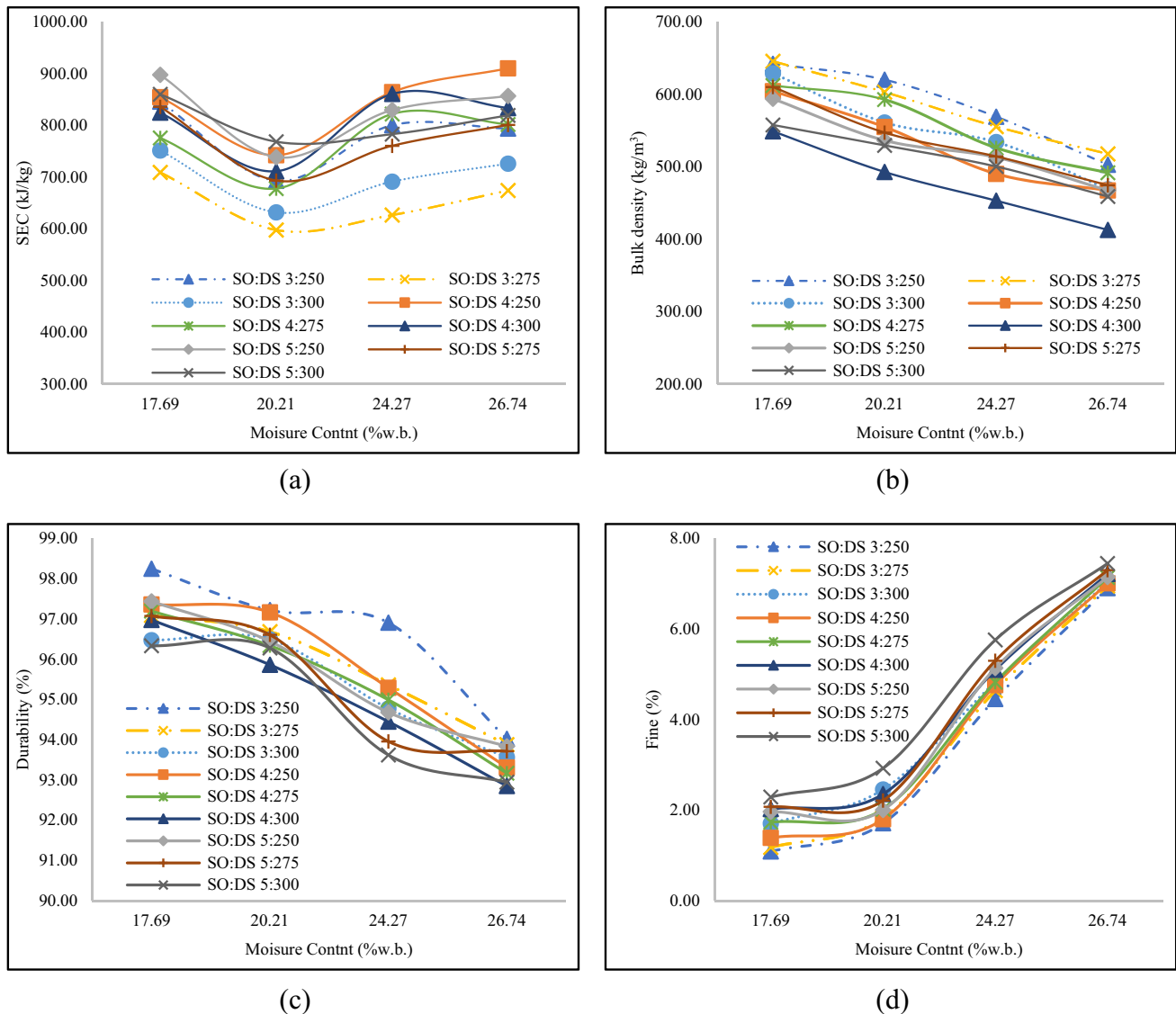The same letter indicates non-significant at LSD test ($\alpha = 0.05$)

Fig. 4 Interaction between eucalyptus powder from each screen size and die speed of each moisture content: **a** SEC, **b** bulk density, **c** durability, and **d** fines (SO/DS = screen size of hammer mill (mm)/die speed of the pelleting machine (rpm))

3.3 Durability and fines

Tables 2 and 3 show the comparison of die speed, screen size, and moisture content affecting the durability of biomass pellets. The size of the screen had no statistically significant effect on durability. While the die speed and moisture content had significant effects on durability. As moisture content increased from 17.69 to 26.74% w.b., the durability decreased (Fig. 4c) because water content in the material and the particles of powder affected the compression and breakage of material. Therefore, durability is reduced and leads to an increase in fines (Fig. 4d). The durability increased as moisture content increased until the durability reached the optimum point. Then, the durability reduced as moisture

content continued to increase. Water has a role in the molecule bonding of particles, which increases durability. In case of low moisture content, there will be space in which the water molecules cannot bond between the particle molecules, resulting in the reduction of durability. On the other hand, high moisture content reduced the durability [55]. However, Tabil Jr and Sokhansanj [59] studied the difference in screen size in a hammer mill (3.2 mm and 6.5 mm) and variability in the durability of alfalfa pellets. They stated that the difference in screen size in the hammer mill did not significantly affect durability. It was consistent with the study of Theerarattananoon et al. [54]. They discovered that the size of the screen in a hammer mill had less of an effect on durability than the die size. In Table 4, the durability should
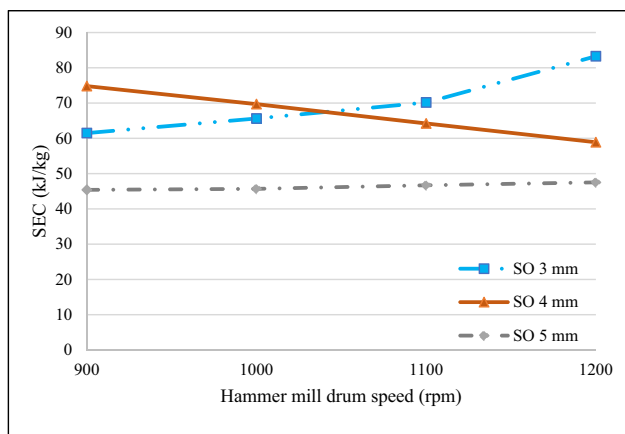
Fig. 5 Relationship between hammer mill drum speed and SEC of eucalyptus bark size reduction for each sieve size (SO = screen size of hammer mill (mm)) [21]

not be lower than 98.0, 97.5, and 97.5% and fines should not exceed 0.1, 0.2, and 0.3%, according to the standard of ENplus A1, ENplus A2 and ENplus B, respectively.

3.4 Diameter and length

The eucalyptus pellets that were sieved through a screen size of 3 mm had a diameter of 6.52 mm and a length of 20.84 mm. The eucalyptus pellets sieved through a screen size of 4 mm had a diameter of 6.52 mm and a length of 22.09 mm. The eucalyptus pellets sieved through a screen size of 5 mm had a diameter of 6.52 mm and a length of 20.49 mm. The diameters and lengths of eucalyptus pellets conformed to the standards for biomass pellets [27].
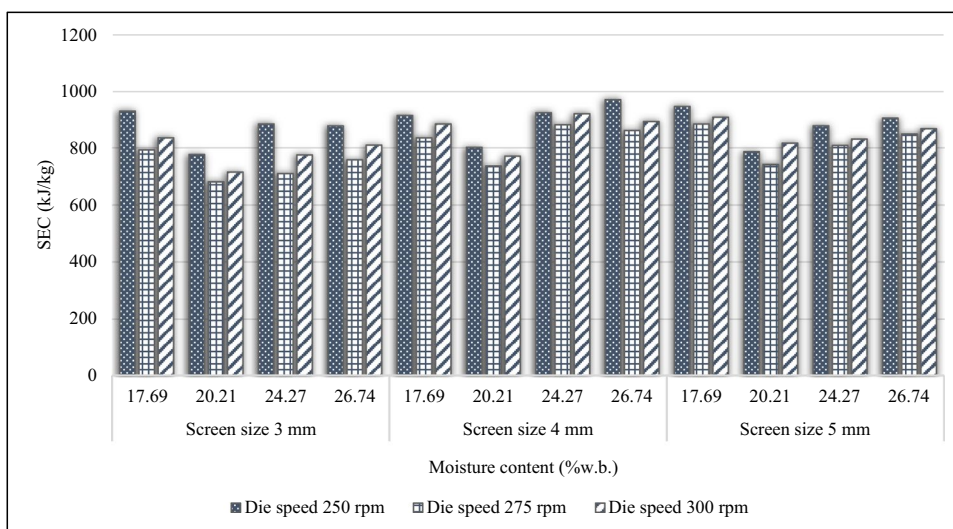
Table 5 summarizes the coefficients for each parameter in the regression analysis, which were represented by Eqs. 7, 8, and 9.

$$BD = 919.969 - 130.472 \times (APS) - 13.412 \times (MC) \quad (7)$$

$$DU = 105.562 - 1.727 \times (APS) - 0.402 \times (MC) \quad (8)$$

$$Fi = -10.642 + 1.485 \times (APS) + 0.615 \times (MC) \quad (9)$$

where BD, DU, and Fi correspond to bulk density, durability, and fines, respectively. APS and MC are defined in Table 5. The standardized factor settings used in the calculations were 0.45, 0.71, and 0.74 for the three levels of average particle size (APS) and 17.69, 20.20, 24.27, and 26.74 for the four levels of moisture contents (MC), respectively. APS and MC were values obtained by analyzing the equation with the studied factors, BU, DU, and Fi, which had R^2 values of 0.735, 0.858, and 94.4, respectively. In general, good models have high R^2 values (close to or equal to 1) [61].

3.5 Energy value of eucalyptus pellets

Table 4 shows the chemical properties of eucalyptus pellets, in which the heating value was 16.19 MJ/kg, meaning they could be used as fuel or supplementary fuel in biomass power plants. According to a report from the Thailand Forest Industry Organization [39], Thailand produced 1.08 million tons of eucalyptus in 2018. The eucalyptus bark residue was 0.22 million tons, with a moisture content of 59.05% w.b. When the moisture content reduced to 17.59% w.b., the eucalyptus bark residue was 0.11 million tons. At a moisture content of 17.59% w.b., the production cost of biomass pellets was 54.43 USD/t or 5.99 million USD/year. The heating value of the eucalyptus pellets (Table 4) was used to

Fig. 6 Specific energy consumed during the production of biofuel pellets from eucalyptus bark for each parameter (hammer mill drum speed of 1200 rpm)

Table 4 Physical and chemical properties of eucalyptus pellets, wood pellets, and biomass pellet standards

Pellet Properties	Unit	Eucalyptus pellets			Wood pellet [60]			Biomass pellet standards		
		Screen size (mm)						ENplus Handbook [27]		
		3	4	5	G. Arborea	A. Mangium	P. Falcataria	ENplus A1	ENplus A2	ENplus B
Moisture content	(% w.b.)	≤10	≤10	≤10	4.1	3.78	4.35	≤10	≤10	≤10
Diameter	(mm)	6.52	6.52	6.52	8.24	8.41	8.13	6, 8 (±1)	6, 8 (±1)	6, 8 (±1)
Length	(mm)	20.84	22.09	20.49	20.68	18.56	26.45	3.15–45 (99% ≤40)	3.15–45 (99% ≤40)	3.15–45 (99% ≤40)
Bulk density	(kg/m^3)	642.13	612.17	610.23	621.24	732.45	687.23	600–750	600–750	600–750
Durability	(%)	98.25	97.36	97.44	98.14	98.48	98.29	≥98.0	≥97.5	≥97.5
Fine	(%)	1.09	1.39	1.96	NA	NA	NA	≤0.1	≤0.2	≤0.3
Heating value	(MJ/kg)	16.19			19.78	19.83	20.10	≥16.5	≥16.5	≥16.5
Energy density	(MJ/m^3)	10,452.04			N/A	N/A	N/A	N/A	N/A	N/A

Table 5 Summary of the coefficients for the different factors in the regression analysis of various responses. APS, average particle size; MC, moisture content; R^2, model's predictive power

Parameter	Constant	APS	MC	R^2
Bulk density (kg/m^3)	919.969	− 130.472	− 13.412	73.5
Durability (%)	105.562	− 1.727	− 0.402	85.8
Fines (%)	− 10.642	1.485	0.615	94.4

calculate the energy gained from the pellets. As a result, the energy gained was 1.78×10^9 MJ/year. When calculated at a boiler efficiency of 38% [51], the energy gained was 6.76×10^8 MJ/year. The total electricity consumption during the biomass pellet production process was 0.97×10^8 MJ/year, so the electrical power obtained from the eucalyptus pellets was 5.79×10^8 MJ/year, which equaled the value of 644 million THB/year or 20.6 million USD/year (0.125 USD/kWh converted from 4 THB/kWh) (Table 6). The preceding information can be used to make decisions concerning the use of eucalyptus pellets to generate electricity for sharing or replacing other biomass materials. This is one of the available strategies for lowering greenhouse gas emissions [62] as well as boosting the economic feasibility of using fuel pellets for energy [63].

4 Conclusion

In this work, eucalyptus bark was crushed to reduce particle size using a hammer mill with screen sizes of 3, 4, and 5 mm, and drum speeds from 900 to 1200 rpm in order to study the physical properties of eucalyptus bark, investigate the crushing process using a hammer mill, and examine the pelletizing factors of biofuel from eucalyptus bark residue using a pellet machine. The eucalyptus powder was pelletized at die speeds from 250 to 300 rpm. The screen size used for particle size reduction affected particle size and specific energy consumption. The die speed and moisture content of the eucalyptus powder affected the properties of biomass pellets.

The particle size decreased when the rotation speed was increased and a smaller screen size was used. The increasing die speed and moisture content of eucalyptus bark resulted in the reduction of bulk density and durability as well as the increase of fines. The study showed the optimal conditions in the pelletizing process for eucalyptus powder from screen sizes of 3 and 4 mm as eucalyptus bark moisture content of 20.21% w.b., hammer mill speed of 1200 rpm, and die speed of 275 rpm. As for eucalyptus powder from a screen size of 5 mm, the optimal conditions were eucalyptus bark moisture content of 17.69% w.b., hammer mill speed of 1200 rpm, and the die speed of 275 rpm. Although the properties of biomass

Table 6 Calculation for the energy value of eucalyptus pellets

Parameter	Calculation	Total
Eucalyptus pellets		
Eucalyptus (million tons/year)	1.08 million tons/year	-
Eucalyptus bark 20%	1.08×0.20	0.22 million tons/year at MC 59.05%
	$0.22 \, (100 - 59.05) / (100 - 17.59)$	0.11 million tons/year at MC 17.59%
Heating value 16.19 MJ/kg	$16.19 \times 0.11 \times 10^9$	1.78×10^9 MJ/year
Power plant efficiency 38%	$0.38 \times 1.78 \times 10^9$	6.76×10^8 MJ/year
Pelletization		
SEC (maximum) (MJ/kg)	$880.70 \times 0.11 \times 10^9$	0.97×10^8 MJ/year
Received energy	$(6.76 \times 10^8) - (0.97 \times 10^8)$	5.79×10^8 MJ/year
Electricity tariff 4 THB/kWh (Thailand)	$((5.79 \times 10^8) / 3.6) \times 4$	644 million THB/year or 20.6 million USD/year

Calculated at the current exchange rate for US dollar (USD) to THAI BAHT (THB) 1 USD = 32 THB

pellets were acceptable and can be the information for use, the impact of the use of biomass pellets should be investigated. The total energy consumption of eucalyptus pellets in biomass pellets was 0.97×10^8 MJ/year, according to the energy analysis of eucalyptus pellets. After deducting energy from production, the pellets for heating the biomass incinerator totaled 5.79×10^8 MJ/year, or 644 million THB/year, or 20.6 million USD/year. The costs of storage and transportation were not included in the calculation. Because this study conducted laboratory testing, additional research on practical application and potential emissions should be conducted.

Declarations

Conflict of interest The authors declare no competing interests.

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