
Sustainable waste valorization of *Cassia fistula* residues for biomass pellet production

Rattanasing, A.¹, Jinnapat, A.² and Tongphanpharn, N.^{3*}

¹Department of Chemistry-Physics, Navaminda Kasatriyadhiraj Royal Thai Air Force Academy, Saraburi, Thailand; ²Department of Military Materials, Navaminda Kasatriyadhiraj Royal Thai Air Force Academy, Saraburi, Thailand; ³Environmental Science Program, Faculty of Science and Technology, Valaya Alongkorn Rajabhat University under the Royal Patronage Pathum Thani Province, Thailand.

Rattanasing, A., Jinnapat, A. and Tongphanpharn, N. (2026). Sustainable waste valorization of *Cassia fistula* residues for biomass pellet production. International Journal of Agricultural Technology 22(5):2393-2406.

Abstract This study focused on converting *Cassia fistula* residues into biofuel pellets as a low-cost biomass energy source. The study pelletized six biomass combinations, including dried leaves, dried branches, and green leaves. All blends achieved a bulk density above 600 kg m⁻³ and a moisture content below 10%. Blend 1 (100% dried branches) was the most suitable biofuel pellet, with a calorific value of 4,364 ± 41.53 cal kg⁻¹, low ash content (4.96 ± 0.28%), and a steady burning rate. In addition, biochemical extractives in green leaves contributed to increasing the heating value; moreover, lignocellulosic biomass enhanced bulk density by acting as a natural binder. The economic feasibility assessment indicated a payback period of 4 years and 8 months, with a positive net present value, confirming the viability of *Cassia fistula* biomass pellet production. Overall, this study highlights the potential of *Cassia fistula* residues for waste valorization, bioenergy production, and reducing greenhouse gas emissions.

Keywords: Biofuel pellets, Renewable energy, Waste to energy, Sustainable application

Introduction

Over the past few years, biomass conversion has become an attractive renewable energy source. (Miranda *et al.*, 2015). Biomass fuel is an alternative to traditional fossil fuels and a sustainable way to reduce greenhouse gas emissions. As a result, many countries have utilized various biomass sources, including agricultural residues, lignocellulosic biomass, and wood waste, to produce pellets and briquettes as solid biofuels. These biomass feedstocks come from diverse sources, including fast-growing trees, perennial grasses, agricultural crop residues, and roadside ornamental waste. Leaf biomass primarily consists of hemicellulose, cellulose, and lignin, along with other carbohydrates, and these biochemical compounds also affect biofuel pellet properties. (Rowell, 2005). Previous studies have reported the potential for bioenergy production from different types of biomass residues, such as sugarcane, soybean straw, coconut husk, coffee residues, and oil palm

* **Corresponding Author:** Tongphanpharn, N.; **Email:** natagarn@vru.ac.th

waste (Soltanian *et al.*, 2019; Huang *et al.*, 2016; Fu *et al.*, 2020; García *et al.*, 2018). Biomass residues not only serve as a valuable feedstock for pellet production but also significantly reduce waste. Furthermore, biomass pellets have higher energy density and are more convenient to transport and store than raw biomass.

Pellets and briquettes are uniform, solid, densified fuels with high energy content and renewability, which have gained popularity in markets (Purohit and Chaturvedi, 2018). In addition, biomass pellets generate fewer particulate emissions than raw biomass or other traditional biofuels (Ghafghazi *et al.*, 2011; Shen *et al.*, 2012). Accordingly, many studies have focused on the physical, mechanical, and chemical properties of pellets to improve pelletization, including using additives as binders and catalysts. For instance, some studies have investigated the effect of agro-residues like eucalyptus sawdust and corn cobs on pellet thermal properties (Kumar *et al.*, 2021). However, the properties of residues generated by biomass pelletization industries remain inadequately characterized. Variability in feedstock composition makes it challenging to ensure consistent pellet quality that meets industry standards.

As interest in waste valorization grows, biomass utilization has shifted toward waste-to-energy strategies to reduce greenhouse gas emissions from fossil fuels. Among various potential feedstocks, *Cassia fistula* Linn., common in South Asia and widely cultivated in tropical regions, offers an opportunity for biofuel production. It is Thailand's national tree, with bright yellow flowers, and is commonly planted along roadsides and in parks. (Chewchinda *et al.*, 2013). However, people typically discard its pods, leaves, and branches as waste, particularly in the summer. *Cassia fistula* has been recognized for its potential in environmental pollution control due to its high carbon content, making it a suitable adsorption material (Sorokhaibam *et al.*, 2015). This highlights the potential to use its waste residues for sustainable applications.

This study focused on the valorization of *Cassia fistula* residues by converting them into biomass pellets. The research aimed to evaluate the physical and chemical properties of pellets produced from different combinations of *Cassia fistula* residues, including bulk density, moisture content, ash content, fixed carbon, and calorific value. Moreover, the study conducted an economic assessment of biomass pellet production to determine the feasibility of using *Cassia fistula* residues as a sustainable biofuel source.

Materials and methods

Biomass preparation

In this study, *Cassia fistula* residues were collected from the Navaminda Kasatriyadhiraj Royal Thai Air Force Academy. The biomass residues,

including dried branches, dried leaves, and green leaves, were mixed in different proportions to evaluate their effects on pellet quality. This study comprised six biomass blends of *Cassia fistula* residues as shown in Table 1, including 100% dried branches (Blend 1), 100% dried leaves (Blend 2), 50% dried branches and 50% dried leaves (Blend 3), 70% dried branches and 30% dried leaves (Blend 4), 50% dried branches and 50% green leaves (Blend 5), and 70% dried branches and 30% green leaves (Blend 6), respectively. Each blend consisted of 10 kg of biomass and was prepared in triplicate ($n = 3$). All *Cassia fistula* residues were air-dried under open conditions and stored at room temperature prior to pelletization.

Table 1. The combinations of *Cassia fistula* residues

Sample	Dried branches (%)	Dried leaves (%)	Green leaves (%)
Blend 1	100	-	-
Blend 2	-	100	-
Blend 3	50	50	-
Blend 4	70	30	-
Blend 5	50	-	50
Blend 6	70	-	30

Biomass pelletization

Prior to pelletization, the biomass residues were dried at 100 °C for 2 hours in an oven to reduce moisture content. The dried residues were then subjected to shredding and grinding to achieve uniform particle sizes. The processed biomass was sieved through a 5x5 mm screen and further refined using a rotary screening system with a 3 mm mesh diameter to ensure consistency in particle size distribution. The wet compression method was used to produce biomass pellets utilizing a ring-die pelletizer (ROTEXMASTER; KN-D-200). The freshly formed pellets were subsequently passed through a cooling process to stabilize their structure. All samples were then stored in sealed plastic bags to prevent moisture loss and potential degradation.

Determination of length and bulk density of biomass pellets

The length and bulk density of all biomass pellets blends were measured following the Solid Biofuels-Fuel Specification and Classes method (ISO EN 14961-1) (European Committee for Standardization, 2010). The length of biomass pellets (approximately 10 grams per sample) was measured using a vernier caliper. Bulk density was determined using a cylindrical container. The container was filled to the top with biomass pellets and weighed using a digital balance. Bulk density was then calculated as the ratio of mass to volume.

Determination of moisture content

Moisture content was determined according to the ASTM D3173 Standard Test Method for Moisture in the Analysis Sample of Coal and Coke (ASTM, 2017a). The method involves measuring the weight loss of a sample when heated under controlled conditions. Prior to analysis, all crucibles were preheated at 105 °C for 30 mins to remove residual moisture. The biomass samples were weighed before being placed in an oven at 105 °C for 2 hours. After heating, the samples were transferred to a desiccator for 20 minutes to prevent moisture absorption before being reweighed. The moisture content was calculated using the following Equation (1):

$$\text{Moisture content (\%)} = \frac{(A-B)}{A} \times 100 \quad (1)$$

Whereas A represented grams of sample before heating and B represented grams of sample after heating.

Determination of ash content

Ash content represents the inorganic residue remaining after complete combustion of biomass pellets. The determination followed the ASTM D3174 Standard Test Method for Ash in the Analysis of Coal and Coke (ASTM, 2017b). First, a porcelain crucible with a cover was preheated at 750 °C for 1 hour, cooled, and then weighed. A 1 g sample of biomass pellets was initially burned at 450–500 °C for 1 hour. The sample was then immediately transferred into the porcelain crucible and further heated at 750 °C for 2 hours. After cooling, the crucible with the remaining ash was weighed, and the ash content was calculated using Equation (2):

$$\text{Ash content (\%)} = \frac{(A-B)}{C} \times 100 \quad (2)$$

Whereas A represents grams of sample and crucible after combustion, B represents grams of the empty porcelain crucible and C represents grams of the initial sample, respectively.

Determination of volatile matter and fixed carbon

Volatile matter was determined by measuring the weight loss of biomass pellets when heated under controlled conditions, following the ASTM D 3175 Standard Test Method for Volatile Matter in the Analysis of Coal and Coke (ASTM, 2017c). A crucible was preheated at 950 °C for 30 mins in the muffle furnace before introducing the biomass sample. The sample was then placed inside the heated crucible, heated at 300 °C for 3 min and increased the temperature to 600 °C for an additional 3 min. The weight

loss before and after heating was used to determine the volatile matter content.

Fixed carbon represents the remaining fraction after moisture, ash, and volatile matter have been removed. The fixed carbon content was determined following the ASTM D3172 Standard Practice for Proximate Analysis of Coal and Coke (ASTM, 2017d). Fixed carbon content was calculated using Equation (3):

$$\text{Fixed carbon (\%)} = 100 - \text{moisture (\%)} - \text{ash (\%)} - \text{volatile matter (\%)} \quad (3)$$

Determination of calorific value

The calorific value, or energy content, of biomass pellets was evaluated according to the ASTM D5865 Standard Method for Gross Calorific Value of Coal and Coke (ASTM, 2017e). The net calorific value was calculated using Equation (4):

$$Q_{p(\text{net})\text{ar}} = Q_{v(\text{gross})\text{ar}} - 5.72 (H_{\text{ar}} \times 9) \quad (4)$$

Whereas $Q_{p(\text{net})\text{ar}}$ = net calorific value at constant pressure (cal kg^{-1})

$Q_{v(\text{gross})\text{ar}}$ = gross calorific value at constant volume (cal kg^{-1})

H_{ar} = total hydrogen content on an as-received basis, where hydrogen and oxygen in sample moisture (%)

Economic evaluation and statistic analysis

The economic feasibility of biomass pellet production was assessed using the payback period method, which determines the time required to recover the initial investment. The payback period was calculated using Equation (5):

$$\text{Payback Period} = (\text{Initial Investment}) / (\text{Net Annual Cash Flow}) \quad (5)$$

Generally, the payback period of no more than five years is considered feasible due to the capital-intensive nature of biomass pelletization, which includes machinery costs, operational expenses, and potential revenue from the biomass pellet market. The investment costs, operating expenses, revenue assumptions, and inflation rates (USD) were integrated into a 10-year feasibility assessment to determine the payback period.

Statistical analysis

In this study, we analyzed the quality of all biomass pellet samples using descriptive statistics and analysis of variance (ANOVA). IBM SPSS Statistics (version 22.0) with a Tukey post hoc test ($P = 0.05$) were used to multiple compare biomass pellet formulations.

Results

Physical properties of biomass pellets

The physical properties of biomass pellets from different blends are summarized in Table 2. The pellets exhibited light brown, brown, and dark brown colors, with lengths ranging from 2.09 to 3.78 cm. Among all blends, 100% dried branches (Blend 1) showed the longest pellet length (3.78 cm). For the bulk density values, all of biomass pellet samples met the ISO EN 14961-1 standards for Solid Biofuels-Fuel specification, with values exceeding 600 kg m^{-3} . Blend 1 showed the highest bulk density ($727.3 \pm 12.1 \text{ kg m}^{-3}$), followed by Blend 4 ($712.3 \pm 7.8 \text{ kg m}^{-3}$). In addition, the moisture content of the biomass pellets ranged from 3.00 ± 0.21 to $5.06 \pm 0.64\%$, remaining well below the 10% threshold established by the ASTM D3173 standard as shown in Table 2.

Table 2. Physical properties of the difference blends biomass pellets

Sample	Length (cm)	Bulk density (kg m^{-3})	Moisture (%)	Color
Standard	0.33–4.50 ^{/1}	> 600 ^{/1}	≤ 10 ^{/2}	
Blend 1	3.78	727.3 ± 12.1	3.00 ± 0.21	light brown
Blend 2	2.47	685.0 ± 3.0	4.92 ± 0.05	dark brown
Blend 3	3.15	681.7 ± 4.6	4.81 ± 0.23	brown
Blend 4	3.29	712.3 ± 7.8	5.06 ± 0.64	brown
Blend 5	2.09	696.0 ± 18.8	4.71 ± 0.28	brown
Blend 6	2.28	690.3 ± 3.1	4.29 ± 0.21	light brown

¹/ISO EN 14961-1

²/ASTM D3173

Chemical properties of biomass pellets

Chemical properties including ash content, volatile content, fixed carbon and calorific values of biomass pellets are shown in Table 3. The ash content of biomass pellets ranged from $4.96 \pm 0.28\%$ to $14.36 \pm 0.61\%$, within the ASTM D3173 standard. Blend 2 (100% dried leaves) exhibited the highest ash content ($14.36 \pm 0.61\%$), followed by Blend 3 ($8.54 \pm 0.34\%$) and Blend 4 ($8.14 \pm 0.66\%$), respectively. The volatile matter content of the biomass pellets ranged from $70.71 \pm 1.10\%$ to $78.42 \pm 0.92\%$. Blend 5 exhibited the highest volatile content ($78.42 \pm 0.92\%$). Meanwhile, fixed carbon refers to non-volatile, combustible carbon found in agro-biomass, ranged from 10.02 ± 1.95 to 15.19 ± 1.63 . Blend 1 exhibited the highest fixed carbon content ($15.19 \pm 1.63\%$), followed by Blend 4 ($14.35 \pm 0.66\%$) and Blend 3 ($13.08 \pm 0.49\%$), respectively. For the calorific value, the highest calorific value of $4,585 \pm 4.92 \text{ cal kg}^{-1}$ was obtained in Blend 5, followed by Blend 6 ($4,423 \pm 11.32 \text{ cal kg}^{-1}$) and Blend 1 ($4,364 \pm 41.53 \text{ cal kg}^{-1}$) (Table 3).

Table 3. Chemical and fuel properties of the difference blends biomass pellets

Sample	Ash (%)	Volatile ^{/4} (%)	Fixed carbon ^{/5} (%)	Calorific value (cal kg ⁻¹)
Standard	≤ 20 ^{/3}			≥ 3,500 ^{/6}
Blend 1	4.96±0.28	76.85±0.90	15.19±1.63	4,364±41.53
Blend 2	14.36±0.61	70.71±1.10	10.02±1.95	4,096±51.38
Blend 3	8.54±0.34	73.57±0.51	13.08±0.49	4,342± 7.59
Blend 4	8.14±0.66	72.45±0.71	14.35±0.66	4,243±24.34
Blend 5	6.04±0.12	78.42±0.92	10.83±0.92	4,585± 4.92
Blend 6	5.70±0.02	77.29±1.06	12.72±1.09	4,423±11.32

³/ASTM D3174⁴/ASTM D3175⁵/ASTM D3176⁶/ASTM D5865***Evaluation of economic feasibility***

This study assessed the economic feasibility of biomass pellet production by evaluating the payback period. The investment cost, operating expenses, and revenue projections were estimated using a 3% inflation rate. Furthermore, the economic feasibility assessed on the assumption basis of the price of biomass pellet, production rate, production period and revenue rate. The cash flow analysis over a 10-year period indicated that the payback period for biomass pellet production was 4 years and 8 months, with a positive net present value (NPV). Generally, for biomass pellet production to be considered economically viable, the payback period should not exceed 5 years (Table 4).

Table 4. Assumption of the investment, the expense, and the revenue of the biomass pellet production

Biomass pellet production	100 kg/hour
Project duration (cash flow investigation)	10 years
Inflation rate	3%
The investment cost	
1) Shredder	5,184.33 USD
2) Pellet mill	5,760.37 USD
The expense	
1) Labour cost	806.45 USD /year
2) Electricity cost	248.85 USD /year
3) Gasoline cost	826.04 USD /year
4) Raw cost	0 USD /year
The revenue ^{/7}	4,147.47 USD/year

⁷/Assumption basis: Biomass pellet price = 0.15 USD/kg

Production rate = 600 kg/day

Production period = 4 days/month

Revenue rate = 34.56 USD/month

Currency exchange rate (May 2023) 1 USD = 34.72 USD

Discussion

Physical properties of biomass pellets

Overall, the physical properties of *Cassia fistula* residues demonstrated the feasibility of producing biomass pellets. Physical properties such as length, bulk density, and moisture content influenced pellet quality. Blend 1 (100% dried branches) exhibited the longest length. This suggests that pellet length increased with the proportion of dried leaves but remained longer than in blends using green leaves (Blends 5 and 6). Bulk density was related to the proportion of branches. This is likely because higher lignin content acts as a binding substrate during pelletization (Panshin and Zeeuw, 1981). This aligns with studies that show lignocellulosic bulk density significantly affects pelletization efficiency (Thiffault *et al.*, 2019). For example, reported bulk density values for lignocellulosic pellet materials range from 435 to 730 kg m⁻³ (Scatolino *et al.*, 2018). Pellet size and biomass type also affect pellet density and tensile strength. Harun and Afzal (2016) found that combinations of feedstocks and sizes resulted in higher bulk density. They reported that blending small-sized spruce or pine (150 mm) with switchgrass produced pellet densities of 900-969 kg m⁻³. Various biomass blends also yielded denser, more combustion-efficient pellets. The high density relates to pellet strength, which refers to the bonding between biomass during pellet production (Mortadha *et al.*, 2025). Higher bulk density improves storage and transportation efficiency. Thus, densification is a crucial factor in biomass pellet quality (Carroll and Finnan, 2012; GUO *et al.*, 2010; Liu *et al.*, 2016). Ideally, biomass pellets should have moisture content below 10% to prevent microbial degradation and loss of structural integrity (Thek and Obernberger, 2012). Moisture levels above 20% can promote bacterial degradation, reduce pellet durability and strength (Kuang *et al.*, 2009), and decrease particle density (Shaw *et al.*, 2009). Moisture content also directly influences combustion efficiency. Higher moisture reduces the calorific value (Carrillo-Parra *et al.*, 2020). Therefore, moisture control is crucial in optimizing biomass pellet quality (Deboni *et al.*, 2019).

Chemical properties of biomass pellets

Biomass pellet quality also depends on chemical properties such as ash content, volatile contents, and calorific values. High ash content can negatively affect pellet quality because it tends to reduce heating values, increase post-combustion residues, and require more furnace maintenance (Serrano *et al.*, 2011). Liu *et al.* (2016) revealed that blending high- and low-ash-content biomass feedstocks can solve these problems. Generally, ash content significantly depends on biomass types; for example, most wood pellets have ash content below 1%, whereas agricultural residues can reach

20% (Saidur *et al.*, 2011), and previous studies reported that the composition of raw biomass significantly influenced ash content, calorific value, and the presence of heavy metals in pellets (Zawiślak *et al.*, 2020). Moreover, a lower ash content is often associated with higher calorific value (Uzun *et al.*, 2017). Thus, optimizing raw biomass composition is a main factor for improving biomass pellet quality.

In this study, the volatile content of *Cassia fistula* pellets varied from $70.71 \pm 1.10\%$ to $78.42 \pm 0.92\%$. Blend 5 (50% dried branches and 50% green leaves) had the highest volatile content ($78.42 \pm 0.92\%$), similar to eucalyptus wood pellets (75- 85%) in a previous study (da Silva *et al.*, 2020). High volatile content influences ignition and consequently improves combustion efficiency. Ghiasi *et al.* (2014) found that volatile matter content in biomass increased after pelletization. In other words, fixed carbon refers to non-volatile matter, generally found in agro-biomass, that burns as combustible carbon. Biomass pellets with higher fixed carbon content tend to burn more steadily, enhancing thermal efficiency (de Paula Protásio *et al.*, 2015), and biomass with high carbon and hydrogen contents was investigated for a higher calorific value (GUO *et al.*, 2010; Telmo and Lousada, 2011). A high fixed carbon content maintains a slow, steady burning rate and sustains heat generation (de Paula Protásio *et al.*, 2013; 2015; Purwanto *et al.*, 2010). Even with high fixed carbon, biomass pellets showed higher heat values and combustion rates; however, previous studies reported that increased volatile matter content during pelletization was associated with decreased fixed carbon content (de Paula Protásio *et al.*, 2013).

Additionally, biochemical components in biomass residues such as cellulose, hemicellulose, lignin, and extractives significantly affected the chemical properties of biomass pellets, likely increasing the calorific value (Kataki and Konwer, 2002). Similarly, da Silva *et al.* (2020) found that sugarcane, bagasse, and elephant grass pellets had higher heating values than commercial wood pellets, likely due to higher extractive contents. The results showed that Blend 5 (50% dried branches and 50% green leaves) and Blend 6 (70% dried branches and 30% green leaves) had high calorific values, likely because the extractives and biochemical compounds in green leaves increased their heating values. Furthermore, calorific value is strongly associated with lignin content (Demirbas, 2004). Serrano *et al.* (2011) also reported that wood-herbaceous biomass blends have low ash and high lignin content, which enhances their calorific value. The biochemical composition of biomass pellets could indicate the combustion efficiency and emissions. For instance, biomass rich in carbon and hydrogen tends to contain more energy (Carroll and Finnan, 2012). In addition, lignin in wood pellets increases calorific value and acts as an additive or binder that strengthens pellets. Additives and binders enhance the durability of biomass pellets and also reduce energy consumption during production (Mortadha *et al.*, 2025). In this study, Blend 1 (100% dried branches) had the highest bulk density ($727.3 \pm$

12.1 kg m⁻³), while Blend 5 (50% dried branches and 50% green leaves) exhibited the highest calorific value (4,585 ± 4.92 cal kg⁻¹). Although Blend 5 had higher ash content and a lower fixed-carbon percentage than Blend 1, it showed superior combustion properties. Therefore, Blend 1 and Blend 5 were identified as the most suitable *Cassia fistula* pellet formulations considered by both bulk density and calorific value. Nevertheless, blends of various biomass pellets and multi-technology pelletization can improve the future physicochemical properties.

Evaluation of economic feasibility and sustainability

This study evaluated the economic feasibility of *Cassia fistula* pellet production and market dynamics, excluding pellet properties and CO₂ emissions. The economic feasibility assessment revealed a payback period of 4 years and 8 months, with a positive NPV. This indicated that *Cassia fistula* residues can be effectively converted into fuel pellets, supporting bioenergy applications and sustaining biomass valorization. Several studies have evaluated the socio-economic impact of utilizing fast-growing tree residues in pellet production and found that *Leucaena*-based pellet production had superior environmental and socio-economic benefits compared to *Acacia*-based pellet production (Saosee *et al.* 2020). Furthermore, life cycle assessment (LCA) of biomass pellets has shown their potential to replace fossil fuels and reduce the carbon footprint of energy production (Mortadha *et al.*, 2025). Zhang *et al.* (2010) reported an LCA study showing that biofuel pellets reduced CO₂ emissions by 90% and 78% compared to coal and natural gas combined-cycle power plants, respectively. Moreover, they reduced SO_x and NO_x emissions by 76-81% and 40-47%, respectively. Although biomass pellets are an attractive clean, renewable energy source, their use and market growth remain limited in Thailand. Driven by energy demand, waste valorization, and sustainability, biomass pellet production has growth potential. Nevertheless, for a comprehensive evaluation of waste-to-energy technologies, future assessments should incorporate waste reduction, CO₂ emission reduction, and the broader bioenergy utilization potential of biomass pellets.

This study evaluated six different combinations of *Cassia fistula* biomass pellets, including their physical and chemical properties and economic feasibility. The results indicated that Blend 1 achieved the highest bulk density (727.3 ± 12.1 kg m⁻³), suggesting proper physical properties, while Blend 5 demonstrated the highest calorific value of 4,585 ± 4.92 cal kg⁻¹, making it a promising biofuel candidate. However, it also had higher ash content and lower fixed carbon compared to Blend 1. Therefore, Blend 1 was the most suitable biomass pellet overall, with a calorific value of 4,364 ± 41.53 cal kg⁻¹, low ash content, and a steady heat rate that ensured efficient combustion. In addition, the biochemical composition of *Cassia fistula*

biomass, including cellulose and hemicellulose in green leaves, affected pellet quality by increasing heating value. Another biochemical compound, lignin, played an important role in improving bulk density during pelletization, acting as a natural binder. The economic feasibility assessment confirmed the viability of *Cassia fistula* biomass pellet production. Overall, valorizing *Cassia fistula* residues offers a promising opportunity for renewable energy production, waste minimization, and greenhouse gas emission reduction, contributing to sustainable bioenergy solutions.

Acknowledgements

This research was supported by the Royal Thai Air Force. The authors would like to express their gratitude to the Navaminda Kasatriyadhiraj Royal Thai Air Force Academy, Faculty of Forestry, Kasetsart University, and Faculty of Science and Technology, Valaya Alongkorn Rajabhat University under the Royal Patronage Pathum Thani Province, Thailand, for the research instruments.

Conflicts of interest

The authors declare no conflict of interest.

References

- ASTM (2017a). Standard Test Method for Moisture in the Analysis Sample of Coal and Coke; ASTM D3173-17a. American Standards and Testing Materials International.
- ASTM (2017b). Standard Test Method for Ash in the Analysis of Coal and Coke; ASTM D3174-12. American Standards and Testing Materials International.
- ASTM (2017c). Standard Test Method for Volatile Matter in the Analysis of Coal and Coke; ASTM D3175-20. American Standards and Testing Materials International.
- ASTM (2017d). Standard Practice for Proximate Analysis of Coal and Coke; ASTM D3172-13. American Standards and Testing Materials International.
- ASTM (2017e). Standard Method for Gross Calorific Value of Coal and Coke; ASTM D5865. American Standards and Testing Materials International.
- Carrillo-Parra, A., Contreras-Trejo, J. C., Pompa-García, M., Pulgarín-Gámiz, M. Á., Rutiaga-Quñones, J. G., Pámanes-Carrasco, G. and Ngangyo-Heya, M. (2020). Agro-pellets from oil palm residues/pine sawdust mixtures: Relationships of their physical, mechanical and energetic properties, with the raw material chemical structure. *Applied sciences*, 10:6383.
- Carroll, J. P. and Finnan, J. (2012). Physical and chemical properties of pellets from energy crops and cereal straws. *Biosystems Engineering*, 112:151-159.
- Chewchinda, S., Wuthi-Udomlert, M. and Gritsanapan, W. (2013). HPLC quantitative analysis of rhein and antidermatophytic activity of *Cassia fistula* pod pulp extracts of various storage conditions. *BioMed research international*, 2013:821295.

- European Committee for Standardization. (2010). EN 14961-1 Solid Biofuels-Fuel Specification and classes, Part 1-General requirements.
- da Silva, S. B., Arantes, M. D. C., de Andrade, J. K. B., Andrade, C. R., Carneiro, A. D. C. O. and de Paula Protásio, T. (2020). Influence of physical and chemical compositions on the properties and energy use of lignocellulosic biomass pellets in Brazil. *Renewable Energy*, 147:1870-1879.
- Deboni, T. L., Simioni, F. J., Brand, M. A. and Lopes, G. P. (2019). Evolution of the quality of forest biomass for energy generation in a cogeneration plant. *Renewable energy*, 135:1291-1302.
- Demirbas, A. (2004). Combustion characteristics of different biomass fuels. *Progress in energy and combustion science*, 30:219-230.
- de Paula Protásio, T., Bufalino, L., Denzin Tonoli, G. H., Junior, M. G., Trugilho, P. F. and Mendes, L. M. (2013). Brazilian Lignocellulosic Wastes for Bioenergy Production: Characterization and Comparison with Fossil Fuels. *BioResources*, 8.
- de Paula Protásio, T., Trugilho, P. F., de Siqueira, H. F., de Melo, I. C. N. A., Andrade, C. R. and Junior, J. B. G. (2015). Caracterização energética de pellets in natura e torreficados produzidos com madeira residual de Pinus. *Pesquisa Florestal Brasileira*, 35:435-442.
- Fu, J., Zhang, J., Jin, C., Wang, Z., Wang, T., Cheng, X. and Ma, C. (2020). Effects of temperature, oxygen and steam on pore structure characteristics of coconut husk activated carbon powders prepared by one-step rapid pyrolysis activation process. *Bioresource technology*, 310:123413.
- García, C. A., Peña, Á., Betancourt, R. and Cardona, C. A. (2018). Energetic and environmental assessment of thermochemical and biochemical ways for producing energy from agricultural solid residues: Coffee Cut-Stems case. *Journal of Environmental Management*, 216:60-168.
- Ghafghazi, S., Sowlati, T., Sokhansanj, S., Bi, X. and Melin, S. (2011). Particulate matter emissions from combustion of wood in district heating applications. *Renewable and Sustainable Energy Reviews*, 15:3019-3028.
- Ghiasi, B., Kumar, L., Furubayashi, T., Lim, C. J., Bi, X., Kim, C. S. and Sokhansanj, S. (2014). Densified biocoal from woodchips: is it better to do torrefaction before or after densification?. *Applied Energy*, 134:133-142.
- GUO, X. J., WANG, S. R., WANG, K. G., Qian, L. I. U. and LUO, Z. Y. (2010). Influence of extractives on mechanism of biomass pyrolysis. *Journal of fuel Chemistry and Technology*, 38:42-46.
- Harun, N. Y. and Afzal, M. T. (2016). Effect of particle size on mechanical properties of pellets made from biomass blends. *Procedia engineering*, 148:93-99.
- Huang, X., Cao, J. P., Zhao, X. Y., Wang, J. X., Fan, X., Zhao, Y. P. and Wei, X. Y. (2016). Pyrolysis kinetics of soybean straw using thermogravimetric analysis. *Fuel*, 169:93-98.

- Kataki, R. and Konwer, D. (2002). Fuelwood characteristics of indigenous tree species of north-east India. *Biomass and Bioenergy*, 22:433-437.
- Kuang, X., Shankar, T. J., Bi, X. T., Lim, C. J., Sokhansanj, S. and Melin, S. (2009). Rate and peak concentrations of off-gas emissions in stored wood pellets-sensitivities to temperature, relative humidity, and headspace volume. *Annals of Occupational Hygiene*, 53:789-796.
- Kumar, P., Subbarao, P. M. V. and Vijay, V. K. (2021). Assessment of pyrolysis-kinetics of corncob and eucalyptus biomass residue using thermo gravimetric analysis. *International Journal of Sustainable Energy*, 40:910-922.
- Liu, Z., Mi, B., Jiang, Z., Fei, B. and Cai, Z. (2016). Improved bulk density of bamboo pellets as biomass for energy production. *Renewable energy*, 86:1-7.
- Mortadha, H., Kerrouchi, H. B., Al-Othman, A. and Tawalbeh, M. (2025). A comprehensive review of biomass pellets and their role in sustainable energy: production, properties, environment, economics, and logistics. *Waste and Biomass Valorization*, 16:4507-4539.
- Miranda, T., Montero, I., Sepúlveda, F. J., Arranz, J. I., Rojas, C. V. and Nogales, S. (2015). A review of pellets from different sources. *Materials*, 8:1413-1427.
- Panshin, A. J. and Zeeuw, C. D. (1981). *Textbook of wood technology*, pp.772.
- Purohit, P. and Chaturvedi, V. (2018). Biomass pellets for power generation in India: a techno-economic evaluation. *Environmental Science and Pollution Research*, 25: 29614-29632.
- Purwanto, W. W., Supramono, D. and Fisafarani, H. (2010). Biomass waste and biomass pellets characteristics and their potential in Indonesia. *Chemical Engineering*, (November), 1.
- Rowell, R. M. (2005). *Handbook of wood chemistry and wood composites*. CRC press.
- Saidur, R., Abdelaziz, E. A., Demirbas, A., Hossain, M. S. and Mekhilef, S. (2011). A review on biomass as a fuel for boilers. *Renewable and sustainable energy reviews*, 15:2262-2289.
- Saosee, P., Sajjakulnukit, B. and Gheewala, S. H. (2020). Environmental and Socio-economic Assessment of Wood pellet Production from Fast growing trees in Thailand. In *IOP Conference Series: Earth and Environmental Science*, Vol. 463, No. 1, p. 012049. IOP Publishing.
- Scatolino, M. V., Neto, L. F. C., Protásio, T. D. P., Carneiro, A. D. C. O., Andrade, C. R., Guimarães Júnior, J. B. and Mendes, L. M. (2018). Options for generation of sustainable energy: production of pellets based on combinations between lignocellulosic biomasses. *Waste and Biomass Valorization*, 9:479-489.
- Shaw, M. D., Karunakaran, C. and Tabil, L. G. (2009). Physicochemical characteristics of densified untreated and steam exploded poplar wood and wheat straw grinds. *Biosystems Engineering*, 103:198-207.

- Shen, G., Tao, S., Wei, S., Zhang, Y., Wang, R., Wang, B., Li W, Shen H., Huang Y., Chen Y., Chen H. and Simonich, S. L. M. (2012). Reductions in emissions of carbonaceous particulate matter and polycyclic aromatic hydrocarbons from combustion of biomass pellets in comparison with raw fuel burning. *Environmental science & technology*, 46:6409-6416.
- Serrano, C., Monedero, E., Lapuerta, M. and Portero, H. (2011). Effect of moisture content, particle size and pine addition on quality parameters of barley straw pellets. *Fuel processing technology*, 92:699-706.
- Soltanian, S., Aghbashlo, M., Farzad, S., Tabatabaei, M., Mandegari, M. and Görgens, J. F. (2019). Exergoeconomic analysis of lactic acid and power cogeneration from sugarcane residues through a biorefinery approach. *Renewable energy*, 143:872-889.
- Sorokhaibam, L. G., Bhandari, V. M., Salvi, M. S., Jain, S., Hadawale, S. D. and Ranade, V. V. (2015). Development of newer adsorbents: activated carbons derived from carbonized *Cassia fistula*. *Industrial & Engineering Chemistry Research*, 54:11844-11857.
- Thek, G. and Obernberger, I. (2012). *The pellet handbook: the production and thermal utilization of biomass pellets*. Routledge.
- Telmo, C. and Lousada, J. (2011). The explained variation by lignin and extractive contents on higher heating value of wood. *Biomass and bioenergy*, 35:663-667.
- Thiffault, E., Barrette, J., Blanchet, P., Nguyen, Q. N. and Adjalle, K. (2019). Optimizing quality of wood pellets made of hardwood processing residues. *Forests*, 10:607.
- Uzun, H., Yıldız, Z., Goldfarb, J. L. and Ceylan, S. (2017). Improved prediction of higher heating value of biomass using an artificial neural network model based on proximate analysis. *Bioresource Technology*, 234:122-130.
- Zawiślak, K., Sobczak, P., Kraszkiewicz, A., Niedziółka, I., Parafiniuk, S., Kuna-Broniowska, I., Tanaś W., Żukiewicz-Sobczak W. and Obidziński, S. (2020). The use of lignocellulosic waste in the production of pellets for energy purposes. *Renewable Energy*, 145:997-1003.
- Zhang, Y., McKechnie, J., Cormier, D., Lyng, R., Mabee, W., Ogino, A. and Maclean, H. L. (2010). Life cycle emissions and cost of producing electricity from coal, natural gas, and wood pellets in Ontario, Canada. *Environmental science & technology*, 44:538-544.

(Received: 22 February 2025, Revised: 8 July 2026, Accepted: 13 September 2026)