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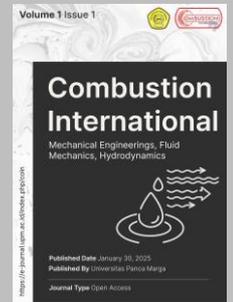
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SUSTAINABLE DEVELOPMENT GOALS

7 AFFORDABLE AND CLEAN ENERGY

Enhancement of Calorific Value in Tectona grandis Sawdust Pellets Using Gossypium spp. Oil and Starch Mixtures

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Abstract

Indonesia's energy demand remains predominantly reliant on non-renewable fossil fuels, including coal, natural gas, and fuel oil, which are utilized extensively across both small and large-scale industries. This reliance exacerbates concerns regarding the finite nature of these resources, their escalating costs, and their detrimental environmental impact. As fossil fuel reserves continue to deplete, the transition to renewable energy sources, such as biomass, becomes imperative. Biomass offers numerous advantages as an alternative fuel; however, its calorific value remains relatively low. This study aims to investigate the potential enhancement of biomass calorific value through the incorporation of Tectona grandis sawdust, Gossypium spp. oil, and starch in varying proportions. An experimental approach was employed, utilizing five different mixtures of teak sawdust, cottonseed oil, and starch: K1 (1 kg:100 g:500 g), K2 (1 kg:250 g:500 g), K3 (1 kg:400 g:500 g), K4 (1 kg:550 g:500 g), and K5 (700 g:500 g). The results indicated a positive correlation between increased cottonseed oil content and higher calorific values, attributed to the reduction in moisture and ash content. The highest calorific value was observed in the K5 mixture, yielding an average value of 4539.492 cal/g.

Keywords: Fossil energy, biomass, calorific value, renewable energy, teak sawdust, cottonseed oil.

1. Introduction

Biomass energy is increasingly viewed as a viable renewable option for electricity generation, heating, and transport, with studies highlighting its economic benefits, job creation, and alignment with the UN Sustainable Development Goals [1], [2]. Technologies such as biomass co-firing in power plants and gasification of

agricultural residues (including palm oil waste) demonstrate practical deployment pathways and economic viability in Indonesia [2], [3]. Substitution of LPG with dimethyl ether (DME) in households, aided by biomass co-processing, further illustrates energy-security benefits and feedstock diversification [4]. Despite a legal basis for renewable energy development, the biomass sector faces permitting, cross-sector coordination, and incentive gaps that hinder implementation; scholars advocate for fiscal incentives and standardization to unlock co-firing and biomass projects [1], [2], [5]. Evidence on emissions is nuanced: biomass energy can contribute to CO2 reductions under proper conditions, but some analyses report a positive link between biomass use and CO2 emissions, albeit modestly [6], [5]. Nonetheless, renewable adoption—including biomass—has been linked to supporting economic growth and energy security in Indonesia [7], [8], with demonstrations showing cost advantages for biomass-based gasifiers and feedstocks like EFB waste and biomass–DME pathways [3], [4].

Torrefaction pretreatment significantly enhances the energy content and fixed carbon of various biomass feeds. For example, oil palm fronds exhibit a calorific value of approximately 23 MJ/kg after undergoing torrefaction at 300°C for 40 minutes, with a blend of 70% torrefied fronds and 30% used bleaching clay reaching peak calorific value, along with a fixed carbon content of around 46% [9]. A similar improvement in both heating value and carbon content is observed for cornstalks, where torrefaction alters the material's kinetics, resulting in a higher energy output [10]. Additionally, mixed-waste biomass briquettes have been shown to achieve very high heating values, such as a combination of dairy sludge and coconut shell achieving a calorific value of approximately 38.7 MJ/kg; however, the resulting high ash content may pose challenges to meeting standard compliance, emphasizing the importance of feedstock and formulation considerations [11]. Blending additives and co-torrefaction can further enhance the heating value and viability of biomass as a fuel source. Specifically, blending herbaceous biomass with woody materials, as well as incorporating plastics, improves the overall quality of pellets and increases the higher heating value (HHV). Moreover, co-torrefaction with plastics has been shown to boost energy yields, even with approximately 20% plastic content [12], [13]. Bio-coal briquettes, which are biomass-coal blends, can significantly elevate energy content while simultaneously reducing emissions, highlighting the contribution of coal-derived char as an energy-dense additive [14]. The selection of feedstock plays a critical role in the energy content of the final product. For instance, plum wood demonstrates the highest calorific value among the fruit-tree woods studied, making it an ideal candidate for pellet and briquette production. Differential scanning calorimetry (DSC) studies further confirm the variability in energy content across different biomass types [15], [16].

In this study, the focus is placed on enhancing the calorific value of biomass pellets made from Tectona grandis (teak) sawdust, a by-product of the woodworking industry, by incorporating Gossypium spp. (cottonseed) oil and starch. These materials were selected due to their availability, low cost, and potential to improve the overall energy density of the biomass. Previous research has shown that cottonseed oil, as a renewable bio-oil, can enhance the fuel properties of biomass by reducing moisture content and improving combustion efficiency. Starch, on the other hand, serves as a binding agent, aiding in the pelletization process and contributing to the structural integrity of the fuel.

This research investigates the effect of varying ratios of teak sawdust, cottonseed oil, and starch on the calorific value, moisture content, ash content, and density of the resulting biomass pellets. The experimental approach used in this study will provide valuable insights into the potential of this biomass mixture as an efficient and sustainable alternative fuel.

2. Methods

2.1 Materials and Biomass Preparation

The primary materials used in this study included Tectona grandis (teak) sawdust, Gossypium spp. (cottonseed) oil, and starch. Teak sawdust was selected as the base biomass due to its availability as a by-product in the woodworking industry. Gossypium spp. oil was chosen for its potential to enhance the fuel properties of the biomass through its high energy content and ability to reduce moisture and ash content. Starch was used as a binding agent to facilitate the pelletization process and improve the structural integrity of the pellets. All materials were sourced locally and were characterized by their moisture content, ash content, and calorific value before use.

2.2 Experimental Design

An experimental approach was employed to investigate the effect of varying ratios of teak sawdust, cottonseed oil, and starch on the calorific value of the biomass pellets. The compositions were prepared in five distinct mixtures (K1, K2, K3, K4, and K5), as shown in Table 1. The ratios of the components in each mixture.

Each mixture was prepared by thoroughly mixing the sawdust, cottonseed oil, and starch in a mechanical mixer to ensure uniformity. The mixture was then subjected to a pelletization process using a pelletizing machine. The pellets were formed by applying pressure through a rotating die system. The pellets were subsequently dried in the sun to reduce moisture content before undergoing carbonization.

Table 1. The experimental design, with the composition ratios for each sample

Mixture	Sawdust (kg)	Cottonseed Oil (g)	Starch (g)
K1	1	100	500
K2	1	250	500
K3	1	400	500
K4	1	550	500
K5	0.7	500	500

2.3 Pelletization and Carbonization Process

The pelletization process was conducted using a mechanical pelletizing machine that operates through a rotating die. The raw mixture of sawdust, cottonseed oil, and starch was introduced into the pelletizer, where it was subjected to compressive force. The pressure applied during pelletization facilitated the binding of the biomass components into a compact, uniform pellet form. After pellet formation, the pellets were subjected to a carbonization process using a custom-built furnace (as shown in Figure 2), which operates at a temperature range of 200°C to 250°C. The carbonization process was carried out for 100 minutes, during which the biomass underwent a transformation into biochar, improving its calorific value by reducing volatile components.

2.4 Analysis of Biomass Properties

The prepared biomass pellets were subjected to comprehensive analysis to evaluate their fuel properties, including calorific value, moisture content, ash content, and density. The calorific value, which is a key indicator of the energy potential of the biomass, was determined using a bomb calorimeter (ASTM D5865-13). In this process, a precise amount of each pellet sample was combusted in a controlled environment, and the heat released during combustion was measured. The resulting data allowed the calculation of the calorific value in calories per gram (cal/g), providing a direct measure of the energy content of the pellets.

To determine the moisture content, the pellets were dried in an oven at 105°C until they reached a constant weight. The moisture content was then calculated as the percentage of weight lost during drying. This property is critical as excess moisture can reduce the energy efficiency of biomass fuels during combustion.

The ash content of the pellets was evaluated by burning the pellet samples in a muffle furnace at 550°C for 6 hours. After the combustion, the remaining ash was weighed, and the ash content was expressed as a percentage of the initial weight of the sample. The ash content is an important factor as higher ash levels can lead to more residue formation during combustion, which may affect the efficiency of biomass as a fuel.

The density of the biomass pellets was also measured, as it is directly related to the fuel's energy density and combustion characteristics. The density was calculated by measuring the volume of each pellet sample using the water displacement method and determining the mass of the sample. The density values provide insight into the compactness of the biomass and its suitability for efficient combustion.

3. Results and Discussion

3.1 Calorific Value

The calorific value of the pellets increased with the proportion of cottonseed oil added to the mixtures. Specifically, the mixture with the highest cottonseed oil content (K5) had the highest calorific value, with an average of 4539.49 cal/g. This suggests that the addition of cottonseed oil improves the energy density of the biomass fuel. The increased calorific value can be attributed to the higher oil content, which contributes to a more energy-dense biomass due to the high calorific value of the oil itself.

The calorific values of the mixtures increased progressively as the proportion of cottonseed oil was increased. The lowest calorific value was found in the K1 mixture (1 kg of sawdust, 100 g of cottonseed oil, and 500 g of starch), with an average of 4208.31 cal/g. In contrast, mixtures with higher cottonseed oil content (K2 to K5) showed increasing values, with the peak being in the K5 mixture (700 g of sawdust and 500 g of cottonseed oil), showing a significant improvement in energy output.

While the increase in cottonseed oil had the most significant impact on the calorific value, the amount of sawdust also plays a role. The K5 mixture, which had a slightly lower amount of sawdust (700 g), showed the highest calorific value, indicating that the additional oil compensates for the lower sawdust content, contributing more to the overall calorific value.

3.2 Density

The data for density (Table 2) show some variation between the mixtures. The highest density was observed in the K5 mixture (1 kg of sawdust and 700 g of cottonseed oil), with an average density of 0.51 g/cm³. This higher density suggests a more compact pellet, which may contribute to better handling and improved combustion properties. Higher density can also indicate that the pellet is less prone to breakage and has a more uniform structure, aiding in more efficient burning.

The K1 mixture (1 kg of sawdust, 100 g of cottonseed oil, and 500 g of starch) had the lowest density, averaging 0.63 g/cm³. This lower density could be due to the higher starch content, which is less compact compared to oil or sawdust, leading to a looser pellet structure.

Table 2. Calorific Value and Density Test Results

Composition	Sawdust (kg)	Cottonseed Oil (g)	Starch (g)	Calorific Value (cal/g)	Density (g/cm³)
K1.1	1	100	500	4212.16	0.64
K1.2	1	100	500	4167.85	0.7
K1.3	1	100	500	4278.45	0.44
K1.4	1	100	500	4181.22	0.7
K1.5	1	100	500	4201.45	0.63
Average	1	100	500	**4208.31**	**0.63**
K2.1	1	250	500	4311.51	0.56
K2.2	1	250	500	4288.7	0.59
K2.3	1	250	500	4268.21	0.59
K2.4	1	250	500	4291.73	0.5
K2.5	1	250	500	4198.27	0.59
Average	1	250	500	**4271.61**	**0.57**
K3.1	1	400	500	4312.91	0.51
K3.2	1	400	500	4387.75	0.58
K3.3	1	400	500	4481.8	0.58
K3.4	1	400	500	4431.31	0.61
K3.5	1	400	500	4321.81	0.64
Average	1	400	500	**4387.12**	**0.59**
K4.1	1	550	500	4451.76	0.57
K4.2	1	550	500	4389.94	0.53
K4.3	1	550	500	4471.22	0.54
K4.4	1	550	500	4492.64	0.31
K4.5	1	550	500	4482.74	0.29
Average	1	550	500	**4457.66**	**0.45**
K5.1	1	700	500	4561.82	0.53
K5.2	1	700	500	4499.21	0.56
K5.3	1	700	500	4531.85	0.5
K5.4	1	700	500	4582.77	0.51
K5.5	1	700	500	4521.81	0.45
Average	1	700	500	**4539.49**	**0.51**

As the cottonseed oil content increased, the density generally decreased in the K2 and K3 mixtures, but as the oil content reached higher levels (K4 and K5), the density stabilized or increased slightly, as seen in **Figure 1**. The K5 mixture's increased oil content likely enhanced pellet compactness, which contributed to the slightly higher density compared to other higher-oil mixtures.

3.3 Moisture Content and Ash Content

The moisture content decreased with increasing amounts of cottonseed oil. The K1 mixture had the highest moisture content, with an average of 12.63%, while the K5 mixture had the lowest moisture content at 4.45%. This reduction in moisture content is advantageous because higher moisture levels in biomass fuels lead to

inefficiencies in combustion and energy loss. The presence of oil likely facilitated the reduction in moisture by absorbing or displacing water molecules in the sawdust.
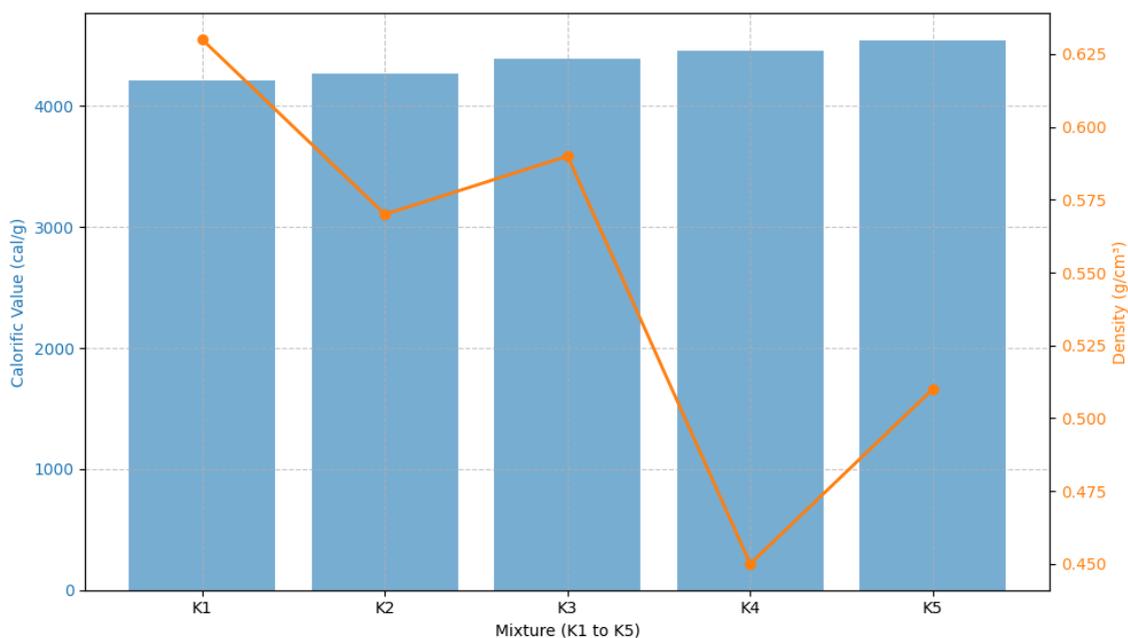

Figure 1. Comparison of Calorific Value and Density for Different Mixtures

Ash content, which affects the residue left after combustion, also showed a noticeable trend. The K1 mixture had the highest ash content at 27.50%, while the K5 mixture had the lowest ash content at 5.17%. This reduction in ash content with increasing cottonseed oil is significant as lower ash content is desirable for improved combustion efficiency and fewer residues after burning. The presence of cottonseed oil likely contributed to reducing the inorganic matter in the sawdust, leading to lower ash formation.

3.4 Overall Trends and Insights

The key takeaway from the data is the substantial impact of cottonseed oil on both the calorific value and physical properties of the biomass pellets. As the oil content increased, the calorific value consistently improved, while moisture and ash content decreased. This suggests that cottonseed oil serves as an effective additive for enhancing biomass fuel properties, making it a promising candidate for improving the energy density of biomass fuels.

The literature on oil-based additives for biomass pellets suggests that the addition of oils, including cottonseed oil, can enhance the energy density and improve various proximate properties of the pellets. While direct data on cottonseed oil as a pellet additive is limited, related studies provide valuable insights. For instance, the addition of waste cooking oil to wood pellets has been shown to increase calorific value by approximately 12–16% and reduce ash content by 16–38%, indicating that oils can improve both the energy content and quality of biomass fuels

[17]. Additionally, co-torrefaction of residual biomass with plastics has resulted in higher heating values (HV) and more favorable ash content, demonstrating the potential of combining different feedstocks to enhance pellet properties [13]. Similarly, blending herbaceous biomass with woody biomass and plastics has been found to improve the HV and overall pellet quality [12], while the torrefaction of oil palm fronds has been shown to significantly increase their energy content (from ~12 MJ/kg to ~23 MJ/kg) [9]. In the context of cottonseed oil, the biodiesel literature highlights the potential of seed-based oils as viable energy feedstocks, although specific pellet-based metrics remain underexplored [18]. Therefore, further research into the use of cottonseed oil as a pellet additive is essential, particularly through methods such as torrefaction or co-torrefaction, to optimize calorific value and improve moisture and ash properties, which could significantly enhance the performance of biomass pellets as a renewable fuel source [19].

The K5 mixture (700 g of sawdust and 500 g of cottonseed oil) represented the optimal formulation in terms of both energy content and physical properties. It showed the highest calorific value and the lowest moisture and ash contents, making it the most suitable for use as an energy-efficient and environmentally friendly biomass fuel.

Based on the findings, further studies could focus on testing other biomass feedstocks with varying additives to explore potential improvements in energy output and fuel efficiency. Additionally, research into the environmental impact of burning these enhanced biomass pellets, including emissions and residue analysis, would provide valuable information for practical applications.

4. Conclusion

This study demonstrates that the addition of Gossypium spp. (cottonseed) oil to Tectona grandis (teak) sawdust biomass pellets significantly enhances their fuel properties. The experimental results indicate that the calorific value of the biomass pellets increases with the proportion of cottonseed oil, with the highest calorific value observed in the K5 mixture (700g sawdust and 500g cottonseed oil), which reached an average value of 4539.49 cal/g. This suggests that cottonseed oil is an effective additive for improving the energy density of biomass fuels, making them more competitive with traditional fossil fuels.

Additionally, the study found that increasing cottonseed oil content led to a reduction in both moisture content and ash content, which are critical factors for combustion efficiency. The K5 mixture showed the lowest moisture content (4.45%) and ash content (5.17%), further indicating its suitability for high-efficiency combustion.

Density measurements also revealed that as cottonseed oil content increased, the pellets became more compact, with the K5 mixture achieving a density of 0.51 g/cm³. This higher density contributes to better handling and a more uniform burn.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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