

POTENTIAL PRODUCTION AND CHARACTERIZATION OF CHARCOAL-BASED BIO-BRIQUETTES FROM ULIN WOOD WASTE AS AN ALTERNATIVE SUSTAINABLE ENERGY RESOURCE

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ABSTRACT

A biomass of Ulin wood waste in tropical countries has significant potential as the raw material used for an alternative sustainable energy resource. This is due to its high technical, economic value, and environmental friendliness. This study aims to develop Ulin wood briquettes using tar extracted from Acacia bark as a binder to form solid cylindrical bio-briquettes. The methodology includes the variation of the pyrolysis temperature (300 - 500°C), the pyrolysis time (3 - 5 h), and the composition of the binder relative to the total mass of the briquettes (91 - 95 %). The briquettes were analysed in terms of yield, moisture content, ash content, volatile matter, fixed carbon, optimum conditions, and surface morphology. The briquettes were also tested for their suitability according to international standard including calorific value, relaxation density, drop test, and combustion rate. The results show that the best quality briquettes based on the mixture of Ulin charcoal and Ulin sawdust with tar binder were found with a variation of 91 % Ulin charcoal and a burning time of 5 h. The best quality variation of Ulin charcoal briquettes produced a calorific value of 7161.26 cal g⁻¹, a moisture content of 2.17 %, an ash content of 2.46 %, a volatile matter content of 15.19 % and a fixed carbon content of 81.11 %. The briquettes produced comply with the quality standards of the ASTM (American Society for Testing and Materials) standard D2395-2007a and SNI (Indonesia National Standard) 01-6235-2000.

Keywords: Ulin wood waste, bio-briquette, biomass, tar, Acacia bark.

INTRODUCTION

The increasing world demand for energy and more significantly the need to minimize the consumption of non-renewable energy sources such as fossil fuels have put a sharper focus on renewable sources of energy. Biomass is one of such attractive sources due to its flexibility and renewability; furthermore, if it can be converted into solid forms of fuel like briquettes. Briquettes are prepared from agricultural and forestry waste. They thus offer an excellent renewable energy source along with reducing the problems associated

with waste management. Logging and processing of Ulin wood (*Eusideroxylon zwageri*) from native, dense, and strong wood in tropical countries such as Indonesia, creates large amount of waste. Although Ulin wood waste has excellent potential to be used as a fuel, most of this waste is simply thrown away, either by burning or throwing it; thus, its potency of energy has not been utilized optimally.

One of the latest studies on the production of briquettes from various sources of wood waste resulted in improved fuel quality such as energy content and combustion efficiency [1 - 3]. However, its utilization

for Ulin wood waste has not been well studied. This current work is intended to address this gap by looking into the feasibility of biomass briquettes production from Ulin wood waste. This work also studies at how the adhesives made from natural adhesive, acacia (*Acacia auriculiformis*) bark tar, could enhance the physical characteristics of the briquettes [4, 5]. In many adhesive applications, acacia bark has been used in the past as a rich source of tannins, whereas the possibilities for binder of briquetting have not yet been fully realized.

The briquettes quality will depend mainly on the binder, which imparts strength and influences their behaviour during combustion [6, 7]. Even though traditional binders such as starch and clay work well, they tend to lower the energy content and increase the ash content in the final product. Acacia bark tar could be beneficial due to its sticky nature, thus increasing the density of energy in the briquette and their strength [8].

The study aims to find improvements in the briquetting process by optimizing parameters such as pyrolysis temperature, quantity of binder, and pressing condition for the production of briquettes that meet quality standards according to ASTM (American Society for Testing and Materials) standard D2395-2007a and SNI (Indonesia National Standard) 01-6235-2000 of wood and wood-based materials.

The commercial success of the briquettes depends on meeting these criteria. Meeting these criteria can be difficult, according to previous research, especially in relation to non-traditional binders or unusual biomass sources [9]. This study provides an implementable way

to deal with the forest debris of any tropical countries and encourages the investigation of sustainable energy source. The work aims to offer briquettes that are not only environmentally friendly but also affordable briquettes through improvement of the manufacturing techniques. These studies will primarily involve the two issues of waste management and renewable energy, converting Ulin wood waste into high-quality bio-briquettes. Even, in forest-rich areas, the data could also provide analysis on the use of large amounts of bio-briquettes as a form of renewable energy.

EXPERIMENTAL

Materials

The materials used in this research included Ulin wood waste sourced from Banjarbaru, South Kalimantan, and Acacia bark, which was used to extract tar to act as a natural binder in making bio-briquettes. Ethanol, filter paper and aluminium foil were also used. Essential equipment for the research included a muffle furnace for pyrolysis at different temperatures, a bomb calorimeter for measurement of the calorific value of the briquettes, a vacuum rotary evaporator for concentration of the acacia bark extract, and a scanning electron microscope (SEM) for analysis of the surface morphology of the briquettes. A wood crusher, a hammer mill, a disc mill and a press were also used for the preparation and shaping of the briquettes. The research was carried out with the use of both fixed and independent variables. The fixed variables included the composition of the Ulin wood charcoal

Table 1. Variables used in making briquettes.

Variable category	Parameter	Detail
Fixed variable	Composition of Ulin wood charcoal and sawdust	1 : 1 (15 g each)
	Pressing pressure	12 psi
	Pressing time	5 min
	Drying temperature	50°C and 100°C
	Briquette dimensions	4 cm in length, 3 cm in diameter
Independent ariables	Lignin-Tannin mixture composition	91 - 95 % (Ulin wood waste to tar ratio)
	Pyrolysis temperature	300 - 500°C
	Pyrolysis time	3 - 5 h

and sawdust (15 g each). The pressing pressure was set at 12 psi, the pressing time was 5 min, the drying temperatures were 50°C and 100°C, and the briquette dimensions were 4 cm in length and 3 cm in diameter. Pyrolysis temperatures of 300 - 500°C, pyrolysis time of 3 - 5 h, and the composition of the binder relative to the total mass of the briquettes (91 - 95 %) were used as independent variables.

Acacia bark extraction

The acacia bark was initially reduced in size and subjected to drying at a temperature of 50°C to reduce the moisture content. Subsequently, the dried bark was pulverized and filtered through a 60-mesh sieve, resulting in a fine powder. To facilitate the extraction process, 75 g of the acacia bark powder was combined with ethanol in a 1 : 10 ratio. Subsequently, the mixture was heated and stirred to facilitate the extraction of tannins, after which filtration was employed to remove any solid residues. The liquid extract was concentrated using a vacuum rotary evaporator at 70°C and subsequently dried at 100°C for one hour, resulting in a thick tar. This was employed as a natural binder for the briquettes.

The yield from acacia bark tar extraction is a crucial indicator of the efficacy of the extraction process. It is calculated by comparing the mass of the extracted tar to the initial mass of the acacia bark employed. A higher yield percentage signifies enhanced efficiency in the extraction, indicating a greater proportion of the acacia bark's potential was successfully transformed into tar. The extraction yield can be determined using the Eq. 1.

$$\text{Yield (\%)} = \frac{\text{Mass of Extracted Tar (g)}}{\text{Initial Mass of Acacia Bark (g)}} \times 100\% \quad (1)$$

The mass of the extracted tar represents the final quantity following the evaporation and drying stages, whereas the initial mass denotes the dry weight of the bark prior to extraction. A higher yield percentage is indicative of enhanced process efficiency. The method ensures that factors such as drying temperature, solvent ratio, and extraction time are optimized to obtain the greatest possible quantity of tar, which in turn enhances the overall efficiency of the briquette production process.

Briquette production

The production process for briquettes entailed the preparation of Ulin wood charcoal and sawdust, both of

which were ground to a fine consistency using a hammer mill and subsequently dried at 50°C for a period of two h. The charcoal and sawdust were combined with acacia bark tar at varying concentrations, ranging from 5 to 9 % by weight. Subsequently, the mixtures were compressed into cylindrical briquettes using a pressing machine at a pressure of 12 psi for a period of five min. The two types of briquettes, prepared from either charcoal or sawdust, were subjected to pyrolysis in a muffle furnace at temperatures of 300 - 500°C for a period of 3 - 5 h, dependent upon the specific experimental conditions. The bio-briquettes were then measured their moisture content, ash content, volatile matter, fixed carbon, caloric value, density, and the mechanical strength of the briquettes.

Pyrolysis optimization

Optimization of the pyrolysis conditions, including temperature and time, was performed using MATLAB R2021b. The optimization process aimed to maximize the fixed carbon content while minimizing volatile matter. A Response Surface Methodology (RSM) was used to analyse the influence of the variables, and the optimal conditions were determined by identifying the highest value of the desirability function.

Surface morphology analysis

The surface morphology of the briquettes was analysed using a Scanning Electron Microscope (SEM, JOEL JSM-6500F). This analysis focused on the distribution and integration of the tar binder within the briquette matrix, providing insights into the physical structure and potential binding efficiency of the acacia bark tar.

RESULTS AND DISCUSSION

Yield and tannin content in acacia bark

The extraction yield of tar from acacia bark was determined by calculating the mass of extracted tannin relative to the initial weight of acacia bark used. The yield of 32 % is consistent with previous studies using ethanol as a solvent for tannin extraction. Ethanol is highly effective due to its polar nature, which increases tannin solubility and provides better extraction efficiency than other solvents such as methanol or water. Ethanol serves as an efficient solvent for maintaining high tannin yields and supporting the effectiveness of binders used

in briquette production. Ethanol consistently provides higher yields while maintaining the binder quality needed for biomass production [10]. It is widely recognized for its ability to extract tannins efficiently and is an ideal choice to produce tar binders in biomass briquette applications [11]. The extraction process was carried out at 100°C with a certain concentration at 70°C to optimize tannin recovery and minimize thermal degradation. Higher temperatures can lead to tannin degradation, which consequently can reduce stickiness, but the controlled temperature conditions in this study maintained both the yield and quality of the extracted tannins [12]. This balance between recovery and preservation of tannin properties is essential to ensure adhesive properties, which are critical to the mechanical strength and durability of briquettes during pyrolysis.

Tannins play an essential role in increasing the physical and thermal stability of briquettes by improving the cohesion between particles. Tannins extracted from acacia bark act as natural adhesives, effectively bind particles together and consequently improve the structural integrity of the briquettes. Increasing in particle cohesion is critical for maintaining the shape and mechanical strength of briquettes during high-temperature combustion [13]. The study shows that ethanol is superior to other solvents such as water or methanol, which either result in lower yields or require more complex recovery processes [10]. The simple recovery process of ethanol also supports its use at larger production scales, making it the preferred solvent for tannin extraction in biomass applications.

The amount of 32 % yield as shown in Table 2 further validates tar extracted from acacia bark as a sustainable and effective binder; thus, it contributes to the mechanical strength and performance of briquettes under combustion conditions.

Proximate analysis

The proximate analysis examines moisture content, ash content, volatile matter, and fixed carbon in charcoal and sawdust briquettes. These parameters, as shown in Table 3, are essential for assessing the briquettes' combustion quality and efficiency and must comply with ASTM and SNI standards [14 - 17].

Moisture content

Moisture content influences both combustion efficiency and storage stability of briquettes. High moisture content reduces energy output because additional energy is needed for water evaporation during combustion. Lower moisture content improves combustion because it minimizes energy losses and allows for higher calorific value output. Low moisture content is essential for improving combustion efficiency as it minimizes energy losses during burning of briquettes products [13, 15]. Both ASTM and SNI standards provide strict guidelines for moisture levels to ensure the performance quality of briquettes.

The data in Table 3 shows that moisture content in sawdust briquettes ranged from 7.83 % to 13.12 % which complies with the ASTM standard but exceeds the SNI standard. This means sawdust briquettes may require further drying steps to meet the stricter SNI moisture limit. Charcoal briquettes had moisture content ranging from 2.17 % to 5.61 % which fully complies with both standards of ASTM and SNI. Lower moisture content

Table 2. Yield of Acacia bark tar extraction.

Sampel type	Sample weight, g	Tannin weight, g	Yield, %
Acacia bark	75	24	32

Table 3. Proximate analysis and calorific value of charcoal and sawdust briquettes.

Parameter	Charcoal briquette	Sawdust briquette	Standard, %	
			ASTM	SNI
Moisture, %	2.17 - 5.61	7.83 - 13.12	< 15	< 12
Ash, %	2.46 - 3.03	0.07 - 0.23	< 8.3	< 8
Volatile matter, %	15.19 - 18.94	77.83 - 83.89	< 85	< 80
Fixed carbon, %	78.04 - 81.11	22.00	> 60	> 14
Calorific value, cal g ⁻¹	7161.26	4629.94	> 5000	> 3940

in charcoal briquettes improves combustion efficiency by reducing energy loss during burning and enabling faster ignition and higher heat output [18].

Fig. 1 shows the relationship between pyrolysis temperature, combustion time, and moisture content for both sawdust and charcoal briquettes. As the temperature increases, moisture content decreases for both types of briquettes. The reduction is more significant in charcoal briquettes which show much lower overall moisture content at all temperature ranges. The figure illustrates that charcoal briquettes experienced a rapid drop in moisture content at higher temperatures, especially around 500°C where moisture levels fell below 3 %. This shows that higher temperatures are effective in reducing moisture content and causing briquettes more efficient for combustion [19]. Maintaining low moisture levels allows for faster ignition and more consistent energy release during combustion.

Sawdust briquettes showed a less sharp decrease in moisture content compared to charcoal briquettes. Although higher temperatures reduce moisture, sawdust briquettes retained moisture levels between 7 % and 13 %. This suggests sawdust briquettes retain more water even at higher pyrolysis temperatures which could affect combustion efficiency [19]. Additional drying or optimizing the pyrolysis process could further reduce moisture content and improve energy efficiency during combustion.

The data and Fig. 1 show that charcoal briquettes are more suitable for applications requiring efficient combustion and higher heat output because of their lower moisture content and better drying rates at elevated temperatures. Sawdust briquettes comply with ASTM standards but would benefit from additional drying to meet SNI standards and improve their combustion performance [20].

Ash content

Ash content indicates the amount of non-combustible material remaining after the briquettes have completely burned. Higher ash content reduces combustion efficiency because more residue is left behind and lower ash content is desirable for cleaner combustion and higher energy output. Low ash content ensures less residue during combustion which contributes to a cleaner burning process and greater fuel efficiency [18]. Both ASTM and SNI standards set limits on ash content to ensure quality performance during combustion.

The sawdust briquettes had ash content ranging from 0.07 % to 0.23 %, which remains well below the ASTM and SNI standards. This low ash content indicates that sawdust briquettes perform efficiently leaving minimal residue after burning. Charcoal briquettes had ash content ranging from 2.46 % to 3.03 %, which complies with both ASTM and SNI standards. Although charcoal briquettes had higher ash content than sawdust

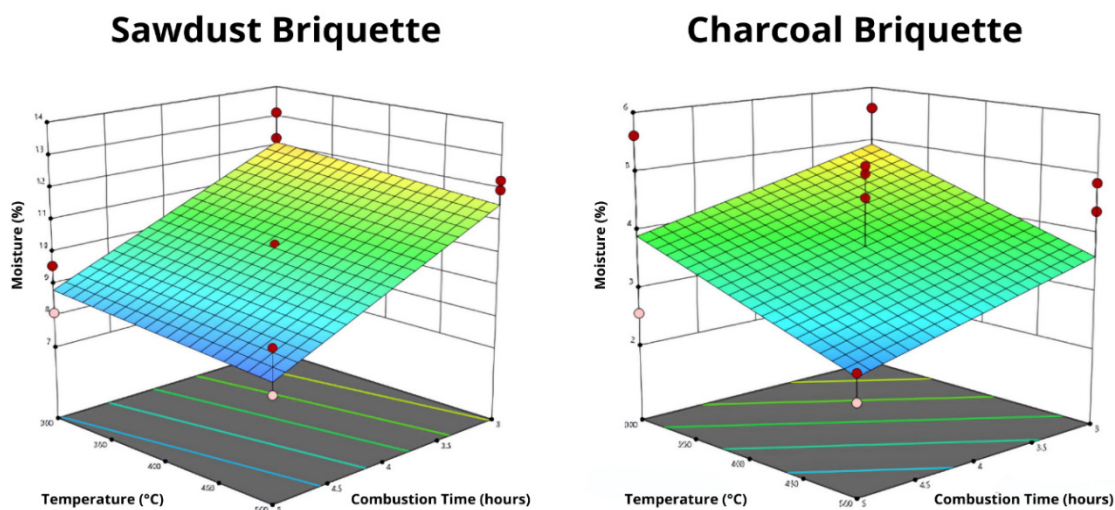


Fig. 1. Effect of pyrolysis temperature on moisture content of sawdust and charcoal briquettes.

briquettes, it is still within acceptable levels for clean combustion and efficient energy use [21].

Fig. 2 shows how pyrolysis temperature and combustion time affect the ash content of both briquette types. The ash content remains relatively stable across all temperature ranges, although charcoal briquettes consistently show higher ash content compared to sawdust briquettes. The ash content of sawdust briquettes stays low across all temperatures and combustion times, remaining below 1 %. This shows that sawdust briquettes have less ash after combustion, resulting in cleaner and more efficient fuel use [17, 21]. Charcoal briquettes show slightly higher ash content across all temperature ranges, but the increase is not significant enough to impact their overall efficiency. The ash content remains between 2.46 % and 3.03 %, which makes charcoal briquettes suitable for applications requiring clean and efficient combustion [22]. Although they produce more ashes than sawdust briquettes, charcoal briquettes still meet the required standards, making them suitable for most industrial and domestic combustion systems. Both sawdust and charcoal briquettes meet the required standards for ash content. Sawdust briquettes, with lower ash content, may be more suitable for applications that require very clean combustion, while charcoal briquettes, with slightly higher ash content, still offer efficient energy use with minimal residue [23].

Volatile matter

Volatile matter refers to the gases released during the initial stages of combustion, influencing how quickly a briquette ignites and the emissions it produces. High volatile matter content tends to accelerate combustion but can also lead to the increased smoke and emissions, which may reduce overall fuel efficiency [24]. Both ASTM and SNI standards regulate the allowable levels of volatile matter to ensure efficient, clean-burning briquettes.

The sawdust briquettes have a relatively high volatile matter content, ranging from 77.83 % to 83.89 %, which meets the ASTM standard, but slightly exceeds the SNI limit. High volatile matter content in sawdust briquettes typically results in faster combustion, which may be advantageous for applications requiring quick ignition but can also lead to higher smoke emissions. This aligns with findings that highlight the trade-off between rapid combustion and clean-burning characteristics when volatile matter levels are elevated [18].

In contrast, charcoal briquettes exhibit significantly lower volatile matter levels, ranging from 15.19 % to 18.94 %, which easily complies with both ASTM and SNI standards that favoured cleaner combustion with fewer emissions [15]. The lower volatile matter content in charcoal briquettes results in slower, more controlled combustion, making them ideal for applications where

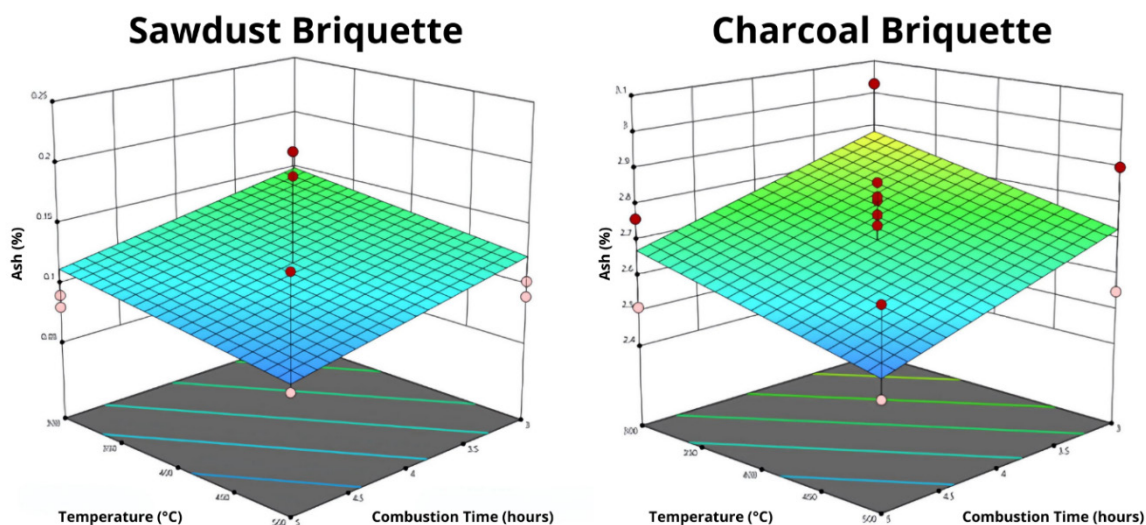


Fig. 2. Effect of pyrolysis temperature on ash content of sawdust and charcoal briquettes.

sustained burning and minimal emissions are critical. The reduced emissions also make charcoal briquettes more suitable for indoor or residential use, where clean combustion is prioritized [25].

Fig. 3 shows the effect of increasing pyrolysis temperature on the volatile matter content for both briquette types. As pyrolysis temperature rises, the volatile matter decreases, particularly for charcoal briquettes. This is consistent with previous research, which shows that higher pyrolysis temperatures facilitate the removal of volatile compounds, resulting in briquettes with more stable and efficient combustion properties [18]. The data and Fig. 3 demonstrate that charcoal briquettes, with their lower volatile matter content, are more suitable for applications where controlled combustion and reduced emissions are necessary. Although sawdust briquettes offer faster combustion due to their higher volatile matter, this can be a disadvantage in settings where clean burning is essential. Adjusting the pyrolysis temperature or drying processes could further reduce the volatile matter in sawdust briquettes, improving their performance [18].

In summary, reducing volatile matter content is essential for optimizing the combustion stability of briquettes. While higher volatile matter may be useful for quick ignition, lower levels are preferable for longer burn times, reduced emissions, and improved energy efficiency. Future studies could focus on optimizing

pyrolysis conditions to balance rapid combustion and emission control, particularly in sawdust briquettes, where slight improvements could enhance their applicability in diverse settings [25, 26].

Fixed carbon

Fixed carbon represents the portion of the briquette that remains after volatile matter has been driven off and moisture has evaporated. It directly influences the calorific value and combustion duration of briquettes, as higher fixed carbon ensures a longer and more stable burn. Fixed carbon is crucial for determining the fuel's energy density, and both ASTM and SNI set specific standards to ensure briquette efficiency [16]. Fixed carbon providing long burn times and high energy output in applications that require sustained heat [18].

The charcoal briquettes contain significantly higher fixed carbon, ranging from 78.04 % to 81.11 %, which exceeds the ASTM standard, and it is consistent with high-performance fuel characteristics. The higher fixed carbon content in charcoal briquettes ensures prolonged combustion, allowing for more consistent energy release over time. This makes them ideal for applications requiring steady heat, such as industrial furnaces or long-duration heating systems [27, 28].

In comparison, sawdust briquettes exhibit a much lower fixed carbon content, measured at 22 %, but only meets the SNI limit. Lower fixed carbon content

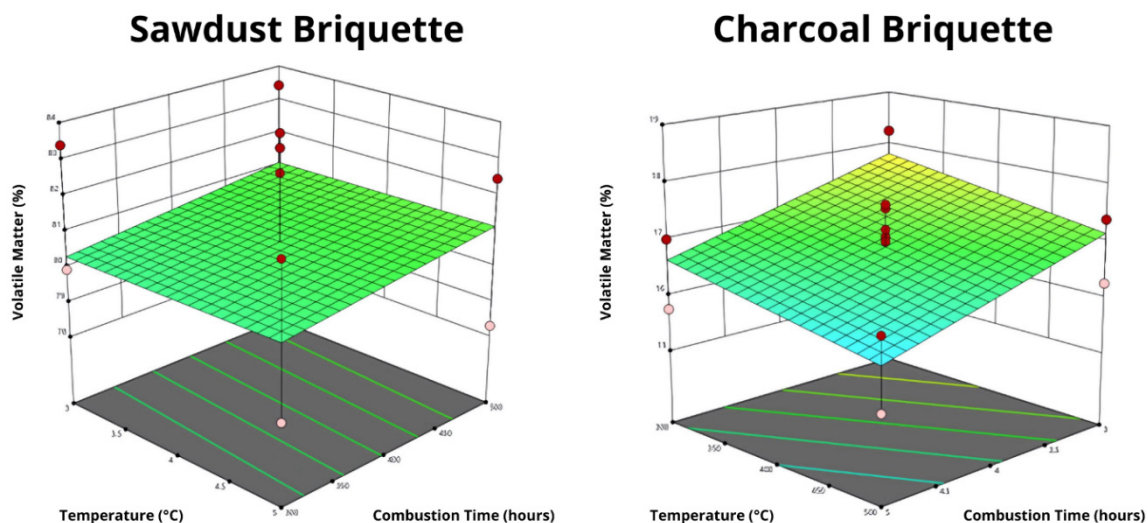


Fig. 3. Effect of pyrolysis temperature on volatile matter content of sawdust and charcoal briquettes.

typically leads to faster burning and shorter combustion times, making sawdust briquettes more suitable for applications requiring quick bursts of energy rather than sustained heat. However, their lower fixed carbon makes them less efficient for high-energy applications where prolonged combustion is necessary [29].

Fig. 4 illustrates the effect of pyrolysis temperature on fixed carbon content in both types of briquettes. As pyrolysis temperature increases, the fixed carbon content rises, particularly in charcoal briquettes, which show a significant increase in carbon content at higher temperatures. This aligns with existing research, which shows that higher pyrolysis temperatures facilitate the breakdown of volatile compounds, leaving behind a more carbon-dense material [19].

The findings from the data and Fig. 4 suggest that charcoal briquettes, with their higher fixed carbon content, are well-suited for high-energy applications that require long-lasting combustion. Sawdust briquettes, although less efficient in producing energy due to their lower fixed carbon, may still serve applications that benefit from faster burning. Adjusting the pyrolysis conditions could potentially increase the fixed carbon content in sawdust briquettes, making them more competitive for broader uses [30].

In conclusion, fixed carbon is a critical parameter for ensuring efficient, long-duration combustion in briquettes. Charcoal briquettes outperform sawdust briquettes in

this aspect, offering longer burn times and higher energy efficiency. However, with optimization in the production process, particularly by increasing pyrolysis temperature, sawdust briquettes could increase in fixed carbon content, thereby expanding their applicability [31].

Calorific value

Although calorific value is not part of the proximate analysis, it is often discussed together due to its importance in assessing the energy potential of briquettes. The calorific value of briquettes is a direct measure of the energy released during combustion, indicating the overall efficiency of the fuel. A higher calorific value signifies that more heat is generated per unit mass, making the briquettes more suitable for high-energy applications. Both standards of ASTM and SNI provide benchmarks to ensure that briquettes meet the necessary energy output requirements [14].

The charcoal briquettes exhibit a significantly higher calorific value of $7161.26 \text{ cal g}^{-1}$, which exceeds both the ASTM and SNI standards. This high calorific value demonstrates their superior efficiency as a fuel source, making them ideal for applications requiring sustained, high-energy output [32]. In contrast, sawdust briquettes have a calorific value of $4629.94 \text{ cal g}^{-1}$, which meets the SNI standard but slightly falls of the ASTM requirement. This suggests that sawdust briquettes are less efficient, but still suitable for lower-energy applications where a

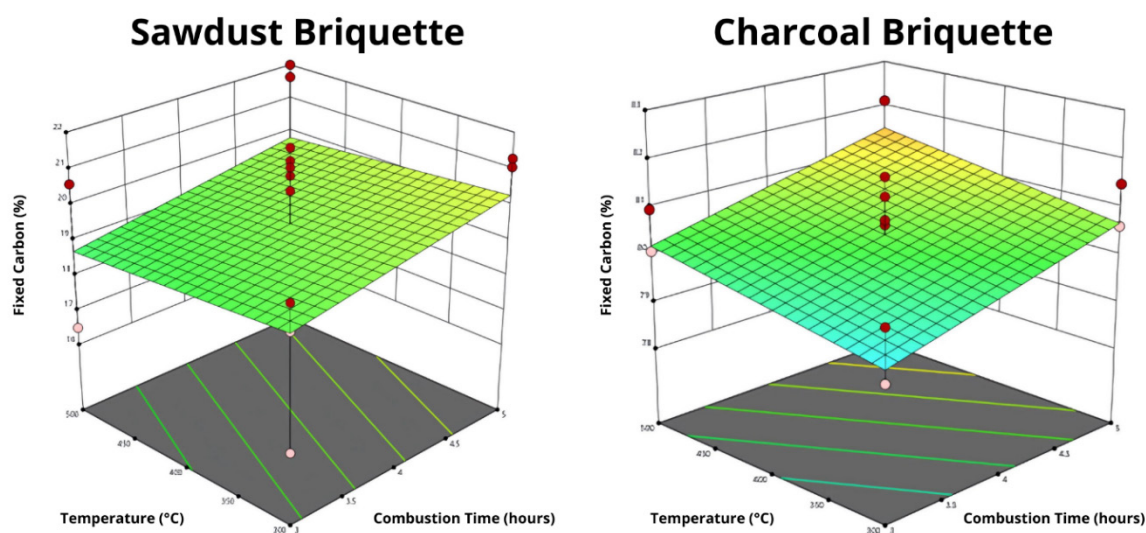


Fig. 4. Effect of pyrolysis temperature on fixed carbon content of sawdust and charcoal briquettes.

rapid energy release is beneficial. The data shows that charcoal briquettes outperform sawdust briquettes in terms of fixed carbon content and volatile matter which makes them more suitable for applications requiring longer combustion times and clean burning. Sawdust briquettes meet most ASTM and SNI standards, but their higher moisture content and volatile matter suggest that they may benefit from additional drying or further optimization to improve overall performance [18].

Fig. 5 depicts the relationship between pyrolysis temperature and the calorific value of both briquette types. As pyrolysis temperature increases, the calorific value of the briquettes rises, especially in charcoal briquettes, which show a marked improvement in energy content at higher temperatures. This result is consistent with previous studies, where increased pyrolysis temperatures result in more complete carbonization, leading to a higher energy output [33].

The findings from the data and Fig. 5 indicate that charcoal briquettes are superior in terms of energy efficiency due to their higher calorific value, making them more appropriate for industrial uses where consistent, high heat output is necessary. Although sawdust briquettes offer a lower calorific value, they are still viable for applications that do not require sustained heat, such as residential heating or small-scale energy needs. Further optimization of the pyrolysis process could improve the calorific value of sawdust briquettes,

enhancing their usability [34].

Overall, the calorific value is a crucial indicator of the energy potential of briquettes. Charcoal briquettes outperform sawdust briquettes, delivering a higher energy output, longer combustion periods, and better efficiency. However, with targeted improvements in production, sawdust briquettes could offer a more competitive calorific value, broadening their application in both industrial and domestic settings.

Physical properties analysis

Density, relaxation performance, and drop test durability are essential physical properties for assessing the mechanical strength, handling stability, and combustion performance of briquettes. These interconnected properties influence the overall durability and efficiency of briquettes in real-world applications [35].

Charcoal briquettes have a higher density ranging from 1.1 to 1.2 g cm⁻³, while sawdust briquettes range from 0.84 to 1.0 g cm⁻³. Higher density in charcoal briquettes indicates better particle packing that minimizes air gaps and allows for slower, more controlled combustion. Increased density enhances combustion efficiency by reducing the rate at which oxygen reaches inner layers. This leads to sustained heat release [36]. Higher density charcoal briquettes display superior energy output, supporting the link between density and combustion efficiency. The relaxation test

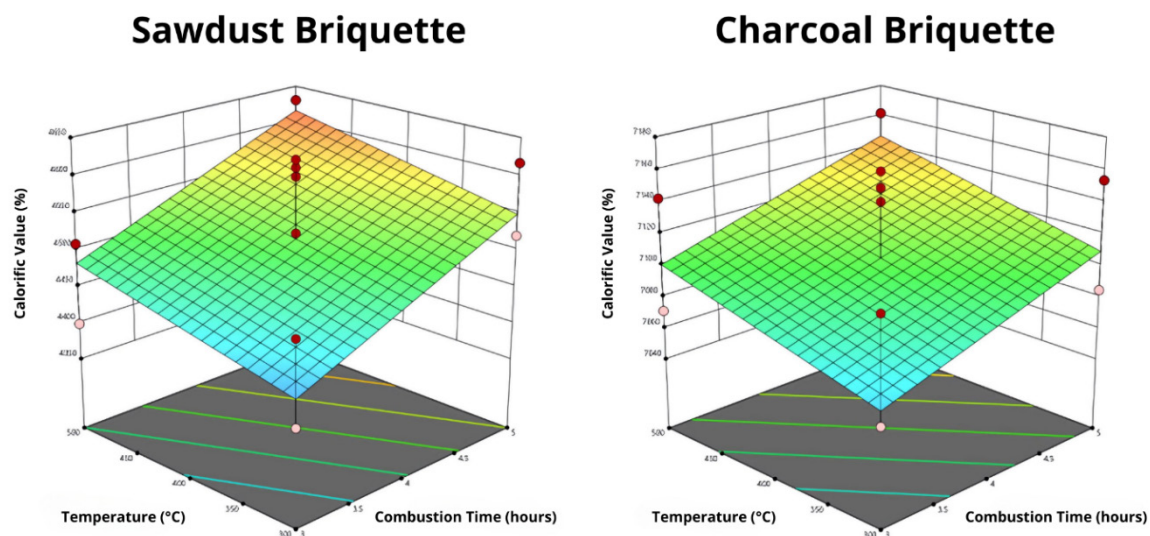


Fig. 5. Effect of pyrolysis temperature on calorific value content of sawdust and charcoal briquettes.

Table 4. Physical properties of charcoal and sawdust briquettes.

Property	Charcoal briquette	Sawdust briquette
Density, g cm ⁻³	1.1 - 1.2	0.84 - 1.0
Mass loss (Relaxation test), %	< 4	< 5
Mass loss (Drop test), %	< 4	< 5

measures the ability of briquettes to retain shape over time. Charcoal briquettes showed less than 4 % mass loss. Sawdust briquettes had slightly higher mass loss at less than 5 %. This difference relates to the higher density of charcoal briquettes that provides greater resistance to deformation [34]. Sawdust briquettes are more prone to minor deformation that can affect mechanical handling.

The drop test simulates transportation conditions. Both charcoal and sawdust briquettes experienced less than 5 % mass loss after being dropped. However, charcoal briquettes performed slightly better with less than 4 % mass loss due to higher density contributing to greater mechanical strength [35]. Denser briquettes are more resilient to rough handling and transportation. This makes them suitable for industrial applications where durability is key [34].

Results from Table 4 illustrate that higher-density briquettes like charcoal are less prone to relaxation and damage during handling while providing improved combustion characteristics. Improving the density of sawdust briquettes could enhance durability and make them more competitive for high-demand applications [26].

The interplay between density and other physical properties is vital. Increased density improves combustion by enabling a longer, controlled burn and strengthens resistance to mechanical damage [27]. The superior performance of charcoal briquettes in both relaxation and drop tests is expected because denser materials offer more stability [24, 37]. The lower density of sawdust briquettes suggests they may benefit from optimization to improve density and mechanical resilience [38].

The charcoal briquettes demonstrate superior physical properties including higher density, better relaxation resistance, and greater durability in the drop test. These features make them suitable for industrial applications where handling durability and combustion efficiency are crucial. Sawdust briquettes are effective but have lower density and slightly higher mass loss, suggesting they are better suited for less demanding

applications. Enhancing the density of sawdust briquettes could improve overall performance, especially in long-term storage and mechanical resilience [16].

Morphological properties

The morphological properties of the briquettes were examined using Scanning Electron Microscopy (SEM) to study the surface structure and the distribution of the acacia bark tar binder. Morphological analysis is essential to understand the mechanical strength, combustion efficiency, and durability of the briquettes, as the microstructure directly impacts how oxygen interacts with the material during combustion and how well the briquettes retain their structural integrity under stress [35].

Fig. 6 presents SEM images showing significant differences in the microstructures of sawdust and charcoal briquettes. The charcoal briquettes display a dense and uniform structure with minimal visible pores, suggesting excellent particle packing and fewer air gaps. This compact structure contributes to their superior density and performance in the relaxation and drop tests. By minimizing the spaces between particles, the briquettes slow down the oxygen infiltration, allowing for more controlled and efficient combustion [39].

In contrast, sawdust briquettes exhibit a porous microstructure with larger voids and less compact particle distribution. This porosity leads to reduced density and quicker combustion, as oxygen can penetrate the briquettes more easily. The higher porosity also explains the higher mass loss in sawdust briquettes during the relaxation and drop tests. This porous nature may result in faster, less efficient burning compared to the denser charcoal briquettes [26, 40].

The acacia bark tar binder distribution also varies between the two briquette types. In charcoal briquettes, the binder is more evenly spread across the surface, enhancing the bonding between particles and contributing to their structural integrity. However, in sawdust briquettes, the binder is less uniformly distributed,

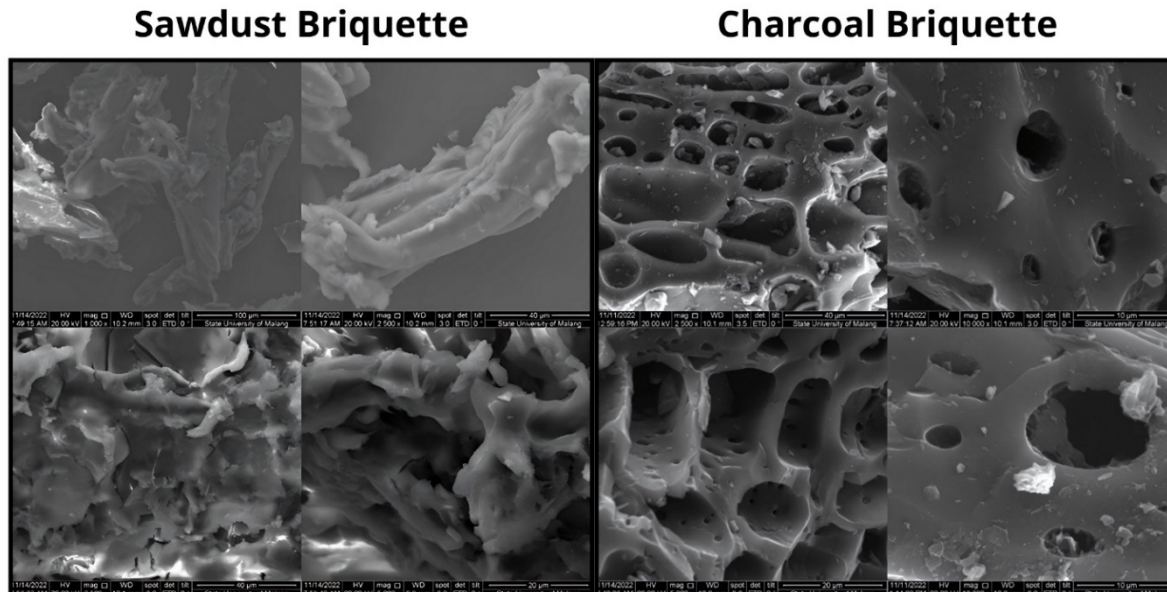


Fig. 6. SEM morphology of sawdust and charcoal briquettes.

leading to weaker bonding and increased deformation during mechanical tests such as the relaxation test [37, 41]. Additionally, pyrolysis temperature plays a crucial role in shaping the microstructure of the briquettes. Charcoal briquettes, processed at higher pyrolysis temperatures, exhibit more carbonized, compact structures, resulting in superior fixed carbon content and calorific value. Sawdust briquettes, produced at lower pyrolysis temperatures, retain more organic material, which corresponds to their lower fixed carbon and calorific output [40, 41].

Fig. 6 also shown reinforce the conclusion that charcoal briquettes, due to their denser structure, are more suitable for applications that require prolonged combustion and higher mechanical durability. Sawdust briquettes, with their more porous structure, are prone to faster combustion and greater mass loss but can be optimized by improving particle packing and binder distribution [26].

CONCLUSIONS

This study demonstrated that charcoal briquettes outperform sawdust briquettes in key performance metrics such as fixed carbon content, volatile matter, calorific value, and physical properties. Charcoal

briquettes exhibited fixed carbon levels ranging from 78.04 to 81.11 % and significantly exceeded the ASTM requirement of more than 60 %. Sawdust briquettes contained only 22 %. The high fixed carbon content in charcoal briquettes contributes directly to prolonged combustion and higher energy efficiency. This is evidenced by a calorific value of 7 161.26 cal g⁻¹ that surpasses both ASTM and SNI standards. Sawdust briquettes showed a calorific value of 4,629.94 cal g⁻¹. Charcoal briquettes had volatile matter content ranging from 15.19 to 18.94 %. This is well below the ASTM limit of 28 % and ensures cleaner combustion with fewer emissions. Sawdust briquettes had volatile matter levels of 77.83 to 83.89 % indicating faster combustion and potentially higher emissions. Charcoal briquettes showed superior mechanical performance in physical properties. Density ranged from 1.1 to 1.2 g cm⁻³ for charcoal briquettes compared to 0.84 to 1.0 g cm⁻³ for sawdust briquettes. The higher density resulted in better particle packing and slower combustion. Morphological analysis based on SEM images highlighted the dense and compact surface structure of charcoal briquettes. This will minimize air gaps and enhances mechanical strength. This makes them ideal for applications requiring long-lasting combustion and mechanical durability. The produced charcoal briquettes showed clear superiority

in fixed carbon content, calorific value, volatile matter, and mechanical strength, thus providing benefits for sustainable energy and strong durability during handling.

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