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# Utilization of Biochar from Catalytic Pyrolysis of Mixed Biomass Waste for Bio Briquette Production

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## Abstract

The increasing depletion of fossil fuel reserves and the need for sustainable energy alternatives have accelerated research on biomass-based briquettes. This study investigates the effect of different catalyst types (6% zeolite, 6% activated carbon, and no catalyst) and binder concentrations (5%, 10%, and 15% w/w) on the physicochemical properties of bio briquettes derived from a mixture of sugarcane bagasse, palm empty fruit bunches (TKKS), and rice husk. Key performance parameters analyzed include moisture content, ash content, and calorific value. The lowest moisture content (2.1%) was obtained using 6% zeolite with 15% binder, while the lowest ash content (5%) was recorded using 6% activated carbon with 5% binder. In terms of energy potential, the highest calorific value (4431.42 cal/g) was achieved with 6% zeolite and 5% binder. However, none of the samples met the SNI 01-6235-2000 calorific value standard (>5000 cal/g), though all met the ESDM minimum threshold (>3500 cal/g), indicating their potential for domestic use. Statistical analysis revealed a quadratic relationship between binder concentration and both moisture and calorific value, highlighting the importance of formulation optimization. The results demonstrate that catalyst type and binder concentration play a critical role in determining the quality of bio briquettes, and a balance between low moisture, minimal ash, and high calorific value must be achieved for practical application. This study supports the development of eco-friendly and renewable solid fuels as a viable substitute for fossil fuels in household energy needs.

## INTRODUCTION

As the global population continues to grow and economies expand, the demand for energy is increasing every day. While advancements in technology have aimed to reduce fossil fuel use, fossil fuels still remain the primary energy source worldwide (Fitriana & Febrina, 2021). According to the Ministry of Energy and Mineral Resources (Nasional, 2023), petroleum fuels are expected to dominate final energy consumption in 2050 at 40.1%, followed by electricity (21.3%), gas (17.7%), coal (11.0%), and the rest such as LPG, biofuels, and biomass each contributing less than 4%.

With fossil fuels becoming scarcer and more expensive, their rising costs are having social and economic impacts on communities. This makes the use of organic materials as alternative heat sources increasingly relevant. Organic materials are a renewable resource, humans can continually produce and replenish them (Rahayu, 2021).

Biomass refers to the total amount of natural material that can be used for both energy and manufacturing purposes. As a renewable

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energy source, it can be converted into solid, liquid, or gaseous fuels. Among the technologies used to harness biomass energy, gasification, liquefaction, and direct combustion are the most common, with direct incineration being the simplest and most widely used in developing countries (Haliza & Saroso, 2023).

One way to increase the value of biomass is by converting it into briquettes. Charcoal briquettes are solid fuels with high energy content and long burn times. Biochar, a key ingredient, is produced by heating dry biomass in the absence of oxygen (Fitriana & Febrina, 2021). Given Indonesia's rich natural biomass resources, exploring briquette production using bio briquette technology holds great potential. Briquettes not only provide a renewable energy source but also help reduce environmental pollution (Gunawan et al., 2022).

The utilization of various biomass residues as raw materials for briquette production has been extensively studied, showcasing a wide range of properties influenced by the type of biomass and the binders used. Harmiansyah et al. (2023) evaluated palm shell briquettes, reporting a moisture content of 6.7% and ash content of 0.20%, both of which satisfied the Indonesian National Standard (SNI). However, the product fell short on volatile matter (34.09%) and fixed carbon (59.1%), indicating that although the thermal stability was promising, the energy content and combustion characteristics still required optimization. This suggests the need for enhanced formulation or post-treatment methods to increase fuel performance.

Yanti et al. (2022) also investigated palm shell biochar combined with tapioca flour as a binder. The resulting briquettes met the SNI 01-6235-2000 quality requirements, showing moisture content values of 4.45% and 4.01%, ash contents of 5.11% and 5.38%, and calorific values of 5999 and 5807 cal/g, respectively. These values indicated good combustion properties and low degradation risk due to moisture. The volatile matter values ranging from 40.49% to 43.50% further confirmed a sufficient proportion of combustible gases, suitable for domestic fuel applications.

Similarly, the study by Ruing & Sulaiman (2022) utilized a blend of palm shell and rice husk (60:40 ratio) with tapioca as a binder, producing a high calorific value of 7.64 kkal, which is equivalent to 7640 cal/g. The combustion rate reached 1.97 g/min, supported by a biomass calorific contribution of 169.78 cal/g. Although the moisture content (10%) and ash content (19.1%) were relatively higher than the SNI recommendation, the energy yield was promising, indicating a good balance between fuel quality and availability of raw materials.

In another investigation, Kamar et al. (2023) explored the potential of corn husk as a briquette feedstock, using jackfruit and pulut sap as binders. Moisture content was observed at 3.176% and 3.332%, and ash content at 6.858% and 7.244%, respectively. The calorific values reached 6136.42 cal/g and 5383.82 cal/g, suggesting that natural resins can act as effective binders while supporting high heat generation and moderate ash production. These results indicated the viability of underutilized agricultural residues when paired with high-bonding organic binders.

Ly et al. (2024) investigated durian shell-based briquettes using an amyl solution and water (1:10 ratio) as the binder. This study found the highest calorific value of 6756.92 kkal/g (equivalent to 6756.92 cal/g), along with a maximum burn time of 64.24 minutes, suggesting extended combustion periods suitable for household energy needs. The optimized condition achieved a calorific value of 5648.12 cal/g with matching burn duration. These findings demonstrate the importance of binder concentration and material porosity in determining energy release efficiency.

Lastly, Anggoro et al. (2018) examined the effect of blending coconut shell and sengon wood sawdust using tapioca binder. It was revealed that the calorific value increased with a higher proportion of biomass with inherently high energy content. This trend was explained through the material's density, moisture, and ash content, aligning with thermochemical principles where higher fixed carbon and lower volatile content contribute to improved thermal behavior. Aristiyanto & Palupi (2014) further confirmed this by utilizing banana peel and sawdust, bound by molasses. The best formulation (10% banana peel and 90% sawdust) achieved 2.06% moisture content, while the best ash value (5%) was obtained at a 25:75 ratio. Notably, the highest calorific value reached 6955.144 cal/g, reinforcing the advantage of molasses as a carbon-rich binder. Based on the previous studies, bio briquette from two different biochar has been explored. However, bio briquette from three different biomass waste biochar with the presence of catalyst has never been done.

This study aims to evaluate the calorific value, ash content, and moisture level of biochar made from a mix of sugarcane bagasse, OPEFB, and rice husks pyrolyzed by using activated carbon and zeolite as catalysts. The results are expected to provide valuable insights into how different catalytic pyrolysis and the binder concentration influence the energy content, physical characteristics, and thermal behaviour of the resulting biomass.

## MATERIALS AND METHOD

### Materials

Materials used in this study was biochar, obtained from the catalytic pyrolysis process of biomass waste mixture which are oil palm empty fruit bunch, sugarcane bagasse and rice husk ash. The biomass wastes were obtained from the local farmer in Indonesia. The catalytic pyrolysis process used two different catalyst which are zeolite 6% (wt/wt) and activated carbon 6% (wt/wt). Tapioca starch was used as a binder obtained from the local market.

### Methods

#### *Preparation of Bio Briquette*

The preparation of the bio briquette was carried out through two main stages: adhesive preparation and briquette formulation. In the first step, the adhesive was prepared by heating 150 mL of water until it reached a temperature of 100°C. Once the water had boiled, 24 grams of tapioca flour were gradually added and stirred until a consistent gel-like adhesive was formed. This adhesive served as the binder in the subsequent briquette production process.

For the briquette preparation, biochar obtained from the pyrolysis of sugarcane bagasse, palm empty fruit bunches (TKKS), and rice husk was first sieved using a 60-mesh sieve to ensure uniform particle size and enhance the bonding efficiency during briquette formation. The sieved biochar was then mixed with the previously prepared tapioca-based binder at different weight ratios, namely 95:5, 90:10, and 85:15 (biochar to binder ratio). The mixture was thoroughly homogenized to ensure even distribution of the binder throughout the biochar particles before being moulded into briquettes and subjected to further analysis.

Following homogenization, the mixture was inserted into a mold and subjected to manual compaction under strong pressure. The molded briquettes were held in the mold for a duration of 5 to 7.5 minutes to ensure structural integrity and increased density. Once pressed, the briquettes were dried in an oven set at 60°C for 3 hours to remove residual moisture and enhance their mechanical strength before being analyzed.

#### *Moisture Content Analysis*

To assess quality, three principal parameters were evaluated: moisture content, ash content, and calorific value. The moisture content was measured using the oven-drying method at 105°C until a constant weight was achieved. The moisture content (%) was calculated using Equation (1).

$$MC\ (\%) = \frac{(W_0 - W_t)}{W_0} \times 100\% \qquad (1)$$

Where, MC is the moisture content, $W_0$ is the initial weight of the bio briquette and $W_t$ is the final weight of the bio briquette. Measurements were performed in triplicate to ensure accuracy and repeatability.

#### *Ash Content Analysis*

The ash content was determined to evaluate the amount of inorganic residue remaining after complete combustion. Approximately 1 gram of dried briquette sample was placed in a pre-weighed porcelain crucible and incinerated in a furnace at 850°C for 4 hours. The remaining ash was weighed after cooling in a desiccator for 30 minutes. The ash content (%) was calculated using Eq. (2).

$$AC\ (\%) = \frac{W_A}{W_0} \times 100\% \qquad (2)$$

Where, AC is the ash content (%), $W_A$ is the ash weight and $W_0$ is the initial weight of the bio briquette. This test was also repeated three times to ensure data reliability.

#### *Calorific Value Analysis*

The calorific value was analyzed using a bomb calorimeter. A pre-weighed briquette sample was placed in the crucible inside the combustion chamber of the calorimeter. The chamber was filled with high-pressure oxygen (25–30 atm), and the system was submerged in water. Upon ignition, the heat released from combustion was absorbed by the surrounding water, and the temperature increase was recorded. The calorific value (Cal/g) was calculated based on Eq. (3).

$$CV\ (Cal/g) = \frac{\Delta T \times Cp_{cal}}{W} \times 100\% \qquad (3)$$

Where, CV is the calorific value (cal/g), $\Delta T$ is the temperature rise, $Cp_{cal}$ is the heat capacity of the calorimeter and W is the sample weight. This measurement provided an indication of the energy content of each briquette formulation.

## RESULTS AND DISCUSSION

### Effect of Binder Concentration on the Moisture Content

Figure 2 illustrates the influence of binder concentration on the moisture content of briquettes under three catalytic conditions: zeolite 6%, activated carbon 6%, and without catalyst. The binder used in this case was tapioca starch, which inherently retains water due to its hygroscopic nature.

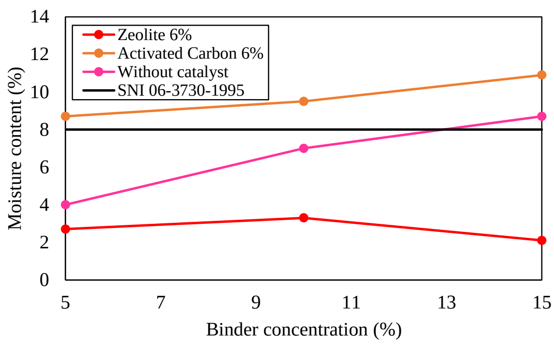


Figure 2. Effect of binder concentration on the moisture content.

Zeolite 6% consistently yielded the lowest moisture content across all binder concentrations, with a minimum at 15% binder (2.1%). Zeolites, known for their high surface area and porosity, can adsorb moisture during pyrolysis and briquette curing, which likely contributes to this observation. Their catalytic properties may also promote more complete devolatilization during pyrolysis, yielding drier biochar (Liu et al., 2025). In contrast, Activated Carbon 6% showed a monotonic increase in moisture content with increasing binder, reaching 10.9% at 15% binder. Although activated carbon is also porous, its performance in this study appears less effective for water removal. This could be due to its higher adsorption of volatile organics or the formation of more hydrophilic surface groups post-pyrolysis. For the briquette from pyrolysis process without catalyst, moisture content also increased with binder addition, but values remained below the activated carbon case, with a peak of 8.7% at 15% binder. This suggests that in absence of catalyst, the effect of increasing starch is more direct. Based on this study, the more binder concentration leads to more retained moisture.

Among all tested combinations, the lowest moisture content (2.1%) was achieved with 6% zeolite catalyst and 15% binder, indicating a promising formulation for producing low-moisture briquettes. The choice of catalyst and binder concentration significantly affects the moisture content of briquettes. Zeolite, particularly at a 6% loading, appears to be more effective in producing briquettes with lower moisture content, which is beneficial for fuel performance since lower moisture enhances combustion efficiency and storage stability.

The increase in moisture content is caused by the addition of water during the preparation of the adhesive material (Saputra et al., 2024). The water contained in the adhesive contributes to the overall moisture content of the briquette during testing. Therefore, the more adhesive added, the higher the moisture content in the briquette. High moisture content in briquettes hinders ignition and lowers the combustion temperature. The calorific value increases as the moisture content decreases. Conversely, higher moisture content results in a lower calorific value (Ariski & Mikhratunnisa, 2023).

According to Yayi et al. (2022), the longer the pressing and drying processes, the more moisture content is removed. This occurs because during pressing and drying, water is expelled from the briquette. In addition, moisture content can also be influenced by the composition of the materials used, as each raw material has its own inherent moisture level. In a study conducted by Iriany et al. (2023), the high moisture content was attributed to the hygroscopic nature of biobriquette particles, which tend to absorb moisture from the surrounding air and environment. It was also suspected that during the experiment, some larger-sized charcoal particles were included, which have more pores and thus a greater capacity to absorb water.

Based on linear regression analysis of the moisture content data, each catalyst shows a distinct relationship with binder concentration. For briquettes using 6% zeolite catalyst, Eq. (4) with $R^2 \approx 0.30$ suggests a slight negative correlation, where moisture content tends to decrease as binder concentration increases. However, the low $R^2$ indicates that this trend is weak and other factors may influence the result.

$$Y = -0.06X + 3.37 \qquad (4)$$

In contrast, the 4% zeolite catalyst follows the Eq. (5) with a high $R^2$ of 0.96, revealing a strong positive linear relationship, meaning more binder leads to significantly higher moisture content.

$$Y = 0.45X + 2.00 \qquad (5)$$

Similarly, for the 6% activated carbon catalyst, the Eq. (6) ($R^2 \approx 0.98$) also confirms a strong positive correlation. These results suggest that while zeolite at lower concentration and activated carbon increase moisture with more binder, 6% zeolite may help suppress moisture, making it a promising candidate for producing low-moisture briquettes.

$$Y = 0.19X + 7.77 \qquad (6)$$

Where, Y is the moisture content (%) and X is the binder concentration.

**Effect of Binder Concentration on the Ash Content**

Ash content is a critical parameter in evaluating briquette quality, as high ash content often leads to incomplete combustion, increased residue, and reduced calorific efficiency. Simultaneously, this analysis also considers the correlation between ash and moisture content, as both factors significantly influence briquette combustion behaviour (Faradaiza et al., 2023). From a thermochemical and practical perspective, an ideal briquette must exhibit both low ash and moisture contents to ensure cleaner, more efficient energy conversion. The effect of binder concentration on the ash content is shown in Figure 3.

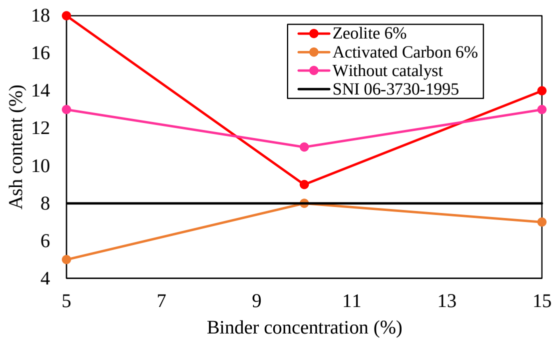

Figure 3. Effect of binder concentration on the ash content.

The ash content results show distinct patterns across the three catalyst conditions. For briquettes produced using zeolite 6% as the catalyst, ash content is significantly high at 18% for 5% binder, drops sharply to 9% at 10% binder, and increases again to 14% at 15% binder. This non-linear behaviour suggests that binder concentration affects the interaction between the zeolite and biomass residue during pyrolysis, potentially due to inconsistent mixing or varying catalytic retention of inorganic content (Lu et al., 2024). In contrast, activated carbon 6% catalyst yielded the most stable and lowest ash contents, with 5%, 8%, and 7% for 5%, 10%, and 15% binder concentrations, respectively. This relatively stable pattern indicates that activated carbon may contribute to a cleaner combustion process due to its higher adsorption capacity and catalytic cracking ability, which reduces residue accumulation (Gayathiri et al., 2022). For the no-catalyst condition, the ash content remained relatively stable, ranging between 11–13%, reflecting typical thermal degradation behaviour without enhanced decomposition of inorganics (Iskandar et al., 2019).

When these ash content results are compared with moisture content data, interesting correlations emerge. For instance, the zeolite 6% catalyst produced the lowest moisture content (2.1%) at 15% binder, but this point coincides with a high ash content of 14%. This suggests that while higher binder improves water retention during moulding, it may facilitate entrainment of inorganic compounds due to zeolite’s porous structure, which traps mineral matter (Tadi et al., 2025). Conversely, activated carbon 6%, though exhibiting the highest moisture content (10.9%) at 15% binder, maintains a low ash content. This may be explained by activated carbon’s high thermal conductivity and porous structure, which enhances devolatilization and gas escape, preventing inorganic residue from accumulating. Thus, the activated carbon's role is more aligned toward improving combustion quality rather than water removal. The no-catalyst samples sit in an intermediate range, showing predictable increases in ash and moisture content with increasing binder, likely due to lack of catalytic assistance in controlling thermal degradation pathways.

Briquettes with lower ash and moisture content are more desirable due to improved combustion efficiency, ease of handling, and minimal residue (Kumar et al., 2021). The findings suggest that activated carbon 6% with 5% binder offers the best combination of low ash (5%) and acceptable moisture content (~8.7%), making it ideal for fuel applications requiring minimal post-combustion cleanup. On the other hand, zeolite 6% catalyst, while favorable in reducing moisture, may inadvertently raise ash levels due to its mineral-rich structure and potential catalytic charring of inorganic biomass components. These trade-offs are crucial when selecting catalysts and binder levels in biomass fuel production. Understanding the dynamic interplay between catalyst type, binder concentration, moisture, and ash content enables researchers and manufacturers to tailor briquette characteristics for specific energy needs and environmental compliance.

**Effect of Binder Concentration on the Calorific Value**

The calorific value of a fuel is a fundamental parameter that determines its energy efficiency, usability, and commercial viability. In the context of biomass briquettes, this value reflects the amount of energy released during complete combustion of the fuel, making it a key indicator of fuel quality. The current study evaluates the calorific value of briquettes made from a combination of sugarcane bagasse, palm empty fruit bunches (TKKS), and rice husk, with varying binder concentrations (5%, 10%, 15%) and three catalyst conditions which are zeolite 6%, activated carbon 6%, and without catalyst. These values are then compared with national standards: SNI 01-6235-2000 and ESDM No. 047 of 2006, which set the minimum calorific value at 5000 kcal/kg and 3500 kcal/kg, respectively. Understanding how different catalyst types and binder concentrations influence calorific value is essential, especially in low-cost alternative fuel production, where achieving efficiency close to fossil fuels remains a significant challenge. Figure 4 shows the effect of binder concentration on the calorific value of the briquette.

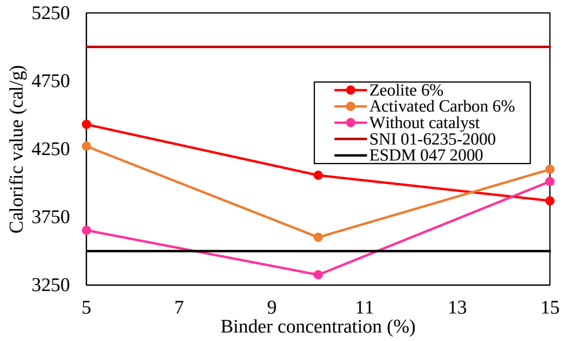


Figure 4. Effect of binder concentration on the calorific value.

The calorific value data shows a complex interplay between binder concentration and catalyst type. At 5% binder, the zeolite 6% catalyst yields the highest calorific value at 4431.42 kcal/kg, followed by activated carbon at 4270.82 kcal/kg, and the lowest is the non-catalyst group at 3652.74 kcal/kg. As binder concentration increases, the calorific value of zeolite-based briquettes decreases significantly, reaching 3868.93 kcal/kg at 15% binder, indicating a strong inverse relationship. Meanwhile, briquettes with activated carbon catalyst show an increase in calorific value from 3600.99 to 4100.3 kcal/kg between 10% and 15% binder, suggesting that higher binder enhances the combustion potential under this catalyst. Interestingly, the non-catalyst group exhibits a linear increase in calorific value with binder concentration, likely due to enhanced structural cohesion and reduced combustion losses. However, none of the samples reach the minimum required calorific value as per SNI standards, though all exceed the ESDM threshold of 3500 kcal/kg, confirming their utility as low-grade alternative fuels.

An insightful perspective is obtained when correlating calorific values with moisture and ash content from the previous analysis. It is well understood that high moisture content leads to energy loss during combustion due to the need to evaporate water before burning actual fuel mass (Lai et al., 2024). Conversely, ash is an inert residue that does not contribute to combustion and may even inhibit it by blocking oxygen flow (Wu et al., 2020). In the case of zeolite 6%, the lowest moisture content (2.1% at 15% binder) corresponds to the lowest calorific value (3868.93 kcal/kg). This indicates that moisture alone does not govern the calorific value. The likely explanation is the high ash content (14%) at this point, which offsets the benefits of reduced moisture. On the other hand, the highest calorific value under zeolite (4431.42 kcal/kg at 5% binder) coincides with a moderately low moisture content (2.7%) and very high ash (18%), suggesting that zeolite may catalyse partial cracking, contributing exothermic reactions that temporarily boost calorific values despite residue accumulation (Chaihad et al., 2022).

Activated carbon-based briquettes tell a different story. Although they carry higher moisture levels (up to 10.9%), their ash content is low (5–8%), which may allow better thermal combustion and heat retention, leading to the observed increase in calorific value at higher binder concentration. For the non-catalyst group, both moisture and ash levels show moderate values, with the calorific value gradually increasing. This suggests that a balanced trade-off between moisture and ash levels may provide relatively better combustion efficiency in the absence of catalytic reactions.

Catalysts like zeolite and activated carbon influence pyrolytic and oxidative decomposition of biomass in different ways. Zeolites, being aluminosilicates with high surface area and acidic sites, facilitate cracking of long-chain volatiles, potentially enhancing gas phase combustion. However, they also trap inorganics, contributing to ash formation, especially at higher binder concentrations, which reduce airflow and hinder combustion (Sun et al., 2025). This explains the inverse trend between calorific value and binder content in zeolite-based briquettes.

Activated carbon, on the other hand, offers a highly porous matrix and better thermal conductivity, promoting complete volatile release and secondary combustion reactions. These characteristics become increasingly effective with higher binder concentrations, which help form a cohesive matrix, slow down devolatilization, and allow more uniform combustion, hence the rise in calorific value with more binder. In the absence of catalysts, combustion relies purely on the intrinsic thermal properties of the biomass and binder, leading to consistent but lower values due to lack of catalytic enhancement.

The role of starch-based binder (tapioca flour) also deserves emphasis. At low concentrations, it aids in particle cohesion without significantly altering combustion behaviour. However, at higher concentrations, it can introduce excess carbon-rich residues that may not burn completely, contributing to ash buildup or inefficient combustion. This effect is particularly visible in zeolite-based briquettes, where the catalyst's ash-retaining nature amplifies this problem.

The findings provide valuable insight into how catalyst selection and binder proportion affect the calorific performance of biomass briquettes. Zeolite-based briquettes, while initially strong in energy release, suffer from ash accumulation and declining energy efficiency at higher binder levels. Activated carbon briquettes, though slightly weaker at low binder levels, improve significantly as binder increases, likely due to better synergy between fuel cohesion and catalytic combustion. These insights are critical when selecting formulations for specific energy needs, especially in regions where biomass waste is abundant but fossil fuels are scarce or expensive.

However, the inability to meet SNI standards suggests further optimization is necessary. Enhancing pre-treatment processes to reduce ash-forming minerals, improving binder properties through additives, or blending catalysts could yield better results. Ultimately, this research confirms that calorific value is a multifactorial outcome, influenced not just by moisture and ash, but also by catalyst chemistry, binder interaction, and particle microstructure. A holistic approach is essential for developing next-generation biomass briquettes with both high efficiency and environmental compliance.

## CONCLUSION

This study explores the production and characterization of bio briquettes from a blend of sugarcane bagasse, palm empty fruit bunches (TKKS), and rice husk using varying binder concentrations and catalytic additives. The comprehensive evaluation focused on three essential parameters (moisture content, ash content, and calorific value) which collectively define the quality and energy potential of bio briquettes. The interplay between binder concentration and catalyst type was found to significantly influence briquette performance, not only through numerical values but also in terms of combustion behaviour, structural integrity, and potential end-use applicability. Zeolite, known for its catalytic cracking and adsorption capabilities, demonstrated promising performance in reducing moisture content, reaching as low as 2.1% at 15% binder. However, this was offset by a rise in ash content and a decline in calorific value, highlighting a trade-off between dryness and combustion residue. Activated carbon, with its high porosity and thermal conductivity, supported more balanced combustion, particularly at higher binder concentrations. It yielded increasing calorific values with a relatively moderate ash buildup, suggesting its suitability for more stable energy output. Interestingly, the binder's role extended beyond cohesion, it interacted with both the catalyst and the biomass matrix to influence energy release and combustion stability. Although none of the briquette formulations met the stringent SNI standard, all exceeded the ESDM minimum, indicating feasibility as alternative domestic fuels. Ultimately, this study underscores that optimal briquette quality is not simply a matter of achieving the best individual values but balancing interdependent variables through material synergy. A holistic approach—considering binder chemistry, catalyst function, and biomass composition—will be critical for advancing biobriquette development as a sustainable and scalable alternative energy source.

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