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Fuel Characteristics of Coconut Shell and Spent Coffee Ground Briquettes Prepared with Different Binders

Unung Leoanggraini, Rasendriya Syahla Putri Prayogo, Azzahra Belle Maerz Alkays, Syahrani Ramawaty, Isma Melani, Rony Pasonang Sihombing*

Department of Chemical Engineering, Politeknik Negeri Bandung, Bandung, Indonesia

*Corresponding Author: rony.pasonang.sihombing@polban.ac.id

Abstract
Coconut shells and spent coffee grounds are biomass residues with potential for conversion into solid fuels through carbonization and densification. Binder selection plays an important role in determining the physical and fuel properties of biomass briquettes. This study evaluated the characteristics of coconut shell and spent coffee ground briquettes prepared using four different binders: tapioca starch, corn starch, poly(vinyl alcohol) (PVA), and Gohsenx Z-200. The raw materials were carbonized at 400 °C for 1 h, ground, and sieved to a particle size of 60 mesh. Coconut shell charcoal and carbonized spent coffee grounds were mixed at a mass ratio of 3:2. The mixture was combined with a 25% binder solution, compacted at 2 ton/cm², and subsequently dried. The resulting briquettes were characterized in terms of moisture content, ash content, volatile matter, fixed carbon, density, and calorific value. The moisture content, ash content, volatile matter, fixed carbon, apparent density, and gross calorific value ranged from 6.60–7.13%, 0.79–1.76%, 0.79–0.92%, 97.45–98.38%, 1.00–1.22 g/cm³, and 6159–6314 cal/g, respectively. Among the tested formulations, tapioca-starch briquettes produced the highest observed gross calorific value of 6314 cal/g and apparent density of 1.22 g/cm³, whereas corn-starch briquettes produced the lowest moisture and ash contents. Therefore, binder performance depended on the selected evaluation criterion, and no single binder demonstrated the best performance for all measured properties.

Keywords: *biomass briquette; coconut shell; spent coffee grounds; binder; carbonization*
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INTRODUCTION

The increasing demand for energy and the continuing generation of agricultural and agro-industrial residues have encouraged the development of technologies that can simultaneously recover energy and reduce the environmental burden of waste disposal. Biomass residues are attractive renewable feedstocks because they are widely available and can be converted into solid, liquid, or gaseous fuels. However, untreated biomass commonly has a low bulk density, irregular particle size, high moisture content, and poor handling characteristics. Densification into briquettes can improve material uniformity, bulk and energy density, transportation, storage, and combustion performance (Kpalo *et al.*, 2020; Ibitoye *et al.*, 2021). Waste-derived briquettes may therefore provide an alternative solid fuel, particularly in regions where agricultural residues are abundant and access to conventional energy sources remains limited (Ferronato *et al.*, 2022).

Coconut shells are a promising briquette feedstock because of their relatively low ash content, high lignocellulosic content, and ability to produce carbon-rich charcoal after thermal treatment. Carbonization removes moisture and part of the volatile constituents while increasing the relative fixed-carbon content and energy density of the resulting char. A review of coconut-derived biochar reported that coconut shell biomass generally has lower ash content and higher fixed-carbon

potential than coconut husk biomass, supporting its conversion into carbonaceous products (Ajien *et al.*, 2023). Yirijor and Bere demonstrated that coconut shell charcoal can be converted into briquettes with high calorific values, although the resulting density, mechanical integrity, ignition behavior, and combustion characteristics depend strongly on the binder type and concentration (Ramadhana *et al.*, 2025).

Spent coffee grounds are another biomass residue with considerable energy potential. Large quantities of this residue are continuously generated by households, cafés, restaurants, and coffee-processing facilities. Improper disposal may increase the organic burden of municipal waste, whereas appropriate valorization can recover residual carbon, carbohydrates, lignin, and oil contained in the material (Kourmentza *et al.*, 2018; McNutt and He, 2019) . Several conversion routes have been investigated, including biodiesel production, anaerobic digestion, extraction of bioactive compounds, pyrolysis, and solid-fuel production (Mata, Martins and Caetano, 2018). From an energy perspective, spent coffee grounds are particularly attractive because their residual oil and carbon contents can provide a gross calorific value exceeding 20 MJ/kg under suitable moisture conditions (Brunerová *et al.*, 2019; Jeníček *et al.*, 2022).

Nevertheless, the production of stable briquettes from spent coffee grounds presents technical challenges. Their residual oil, hygroscopic behavior, and particle characteristics can limit interparticle bonding during compaction. The incorporation of spent coffee grounds into wood-based briquettes has been reported to increase energy potential while reducing mechanical durability, depending on the biomass ratio (Jeníček *et al.*, 2022). Espuelas et al. found that pure spent coffee grounds could not readily form functional briquettes under low-energy densification conditions without a suitable binder (Espuelas *et al.*, 2020). Their findings showed that binder type, binder concentration, moisture content, and compaction pressure jointly influenced briquette density, durability, water absorption, and fuel characteristics. Combining spent coffee grounds with coconut shell charcoal may therefore provide a complementary feedstock system, but an appropriate binder remains necessary to maintain particle cohesion and obtain consistent fuel properties.

Binders facilitate briquette formation by generating interparticle bridges and improving the cohesion of compacted biomass. Their performance is governed by chemical composition, concentration, water requirement, preparation conditions, compatibility with the feedstock, and behavior during combustion (Obi, Pecenka and Clifford, 2022). Starch-based binders such as tapioca and corn starch are widely used because they are accessible, biodegradable, combustible, and capable of developing adhesive properties after gelatinization. However, their hydrophilic nature may increase moisture uptake, while excessive binder addition may dilute the energy-rich fraction of the briquette. Cassava- and corn-starch binders have been reported to produce different density, mechanical-strength, and calorific-value profiles in coconut shell charcoal briquettes [5]. Tapioca starch has also been associated with relatively low ash content and high fixed-carbon content compared with molasses and mineral binders (Seetapong *et al.*, 2024).

Synthetic or semi-synthetic polymeric binders may offer different bonding characteristics. Poly(vinyl alcohol) (PVA) contains abundant hydroxyl groups that can interact with oxygen-containing groups on biomass particles through hydrogen bonding. Its film-forming behavior may improve interparticle adhesion and structural cohesion. Binder-selection studies on thermally treated biomass have confirmed that no single binder performs optimally for every feedstock because the resulting durability and density depend on binder–biomass compatibility (Butler, Skrivan and Lotfi, 2023). More recent research has shown that PVA-based binder systems can improve the compressive strength and moisture resistance of charcoal briquettes, although their performance depends on polymer concentration and particle size (Korol and Yankovych, 2025). Consequently, comparing starch-based binders with PVA-based binders under identical preparation conditions is necessary to clarify their respective effects on the physical and fuel characteristics of mixed-biomass briquettes.

Table 1. Selected studies related to biomass feedstocks and binders used in briquette production

Reference	Feedstock and binder	Main finding	Relevance to the present study
(Jeníček *et al.*, 2022)	Spent coffee grounds blended with sawdust or wood shavings	Spent coffee grounds increased the energy potential but could reduce mechanical durability	Demonstrates the energetic contribution and densification limitations of spent coffee grounds
(Espuelas *et al.*, 2020)	Spent coffee grounds with xanthan or guar gum	Binder dosage, moisture content, and pressure controlled density and durability	Confirms the importance of binder selection for spent-coffee-ground briquettes
(Butler, Skrivan and Lotfi, 2023)	Torrefied biomass pellets with different binders	Binder performance depended on compatibility with thermally treated biomass	Supports comparative evaluation under identical processing conditions
(Ramadhana *et al.*, 2025)	Coconut shell charcoal with cassava- or corn-starch binders	Binder type and concentration affected density, strength, ignition, and calorific value	Provides a direct comparison for starch-bound coconut shell briquettes
(Seetapong *et al.*, 2024)	Palm-shell charcoal with tapioca, molasses, or clay	Tapioca produced relatively low ash and high fixed-carbon contents	Supports the use of tapioca as an organic combustible binder
(Korol and Yankovych, 2025)	Charcoal briquettes with PVA-based binder systems	PVA improved mechanical strength and moisture resistance under appropriate formulation conditions	Provides a basis for evaluating PVA-based binders

Previous studies have generally examined coconut shell charcoal or spent coffee grounds separately, combined spent coffee grounds with wood biomass, or evaluated a limited group of natural binders. Comparative information remains limited regarding the use of starch- and PVA-based binders in briquettes produced from the same mixture of carbonized coconut shells and spent coffee grounds under identical preparation and compaction conditions. Therefore, this study comparatively evaluated briquettes prepared using tapioca starch, corn starch, PVA, and Gohsenx Z-200 as binders. The briquettes were characterized in terms of moisture content, ash content, volatile matter, fixed carbon, density, and calorific value. Where relevant, the measured fuel properties were compared with the requirements of SNI 01-6235-2000 to identify the binder formulation that provided the most favorable overall characteristics within the investigated conditions.

METHODS

Materials and Equipment

The experimental work was conducted at the Industrial Waste Management Laboratory, Analytical Chemistry Laboratory, and Corrosion Laboratory of the Department of Chemical Engineering, as well as the Machining Laboratory of the Department of Mechanical Engineering, Politeknik Negeri Bandung, Indonesia.

Materials and Equipment

The primary raw materials were coconut shells and spent Robusta coffee grounds. The coconut shells were collected from Pasar Atas, Cimahi Tengah, Cimahi, Indonesia, whereas the spent coffee grounds were obtained from a coffee shop on Gandawijaya Street, Setiamanah, Cimahi Tengah, Cimahi, Indonesia. Four different binders were investigated: tapioca starch, corn starch, polyvinyl alcohol (PVA), and Gohsenx Z-200. Clean water was used to prepare the binder mixtures. The principal equipment included a laboratory furnace, drying oven, analytical balance, grinder, 60-mesh sieve, briquette mold, hydraulic press, porcelain crucibles, laboratory glassware, and bomb calorimeter.

Feedstock Preparation

The coconut shells were manually cleaned to remove residual fibers and adhering impurities. Contaminated or visibly deteriorated portions of the spent coffee grounds were discarded. The cleaned coconut shells were subsequently reduced to pieces measuring approximately 1–1.5 cm to facilitate drying and carbonization. The coconut shells and spent coffee grounds were initially sun-dried for approximately two days. Both materials were subsequently dried in an oven at 105°C until a constant mass was obtained.

Carbonization and Particle-Size Reduction

The dried coconut shells and spent coffee grounds were carbonized separately in a furnace at 400°C for 1 h. After carbonization, the resulting coconut-shell charcoal and spent-coffee-ground charcoal were allowed to cool before further processing. Both charcoal materials were ground separately using a laboratory grinder. The resulting charcoal powders were passed through a 60-mesh sieve to obtain a relatively uniform particle size.

Binder Preparation and Briquette Formulation

For each formulation, 30 g of coconut-shell charcoal and 20 g of spent-coffee-ground charcoal were used, corresponding to a charcoal mass ratio of 3:2. The two charcoal powders were mixed until a visually homogeneous blend was obtained. Each binder mixture was prepared using 10 g of binder and 40 mL of water, corresponding to a binder-to-water ratio of 1:4. The binder was gradually added to the charcoal blend and mixed until a homogeneous and moldable mixture was obtained. The compositions of the four briquette formulations are presented in Table 2.

Table 2. Composition of coconut-shell and spent-coffee-ground briquettes

Formulation	Coconut-shell charcoal (g)	Coffee-ground charcoal (g)	Binder type	Binder (g)	Water (mL)
T	30	20	Tapioca starch	10	40
C	30	20	Corn starch	10	40
P	30	20	Polyvinyl alcohol	10	40
G	30	20	Gohsenx Z-200	10	40

The binder accounted for approximately 16.67% of the total dry mass of each formulation. This percentage was determined by comparing the mass of the binder with the combined dry mass of the coconut-shell charcoal, spent-coffee-ground charcoal, and binder. Therefore, the designation of 25% in the initial experimental record refers to the binder-to-water proportion of 10 g per 40 mL rather than the binder percentage in the total dry briquette formulation.

Briquette Molding and Drying

Each charcoal–binder mixture was transferred into a briquette mold and compacted using a hydraulic press at 2 ton-force/cm², equivalent to approximately 196 MPa. This pressure was applied consistently to all formulations to obtain sufficiently consolidated briquettes and to maintain compaction pressure as a controlled processing condition during the comparison of binder types. No separate pressure-optimization experiment was conducted. Therefore, the applied pressure should be regarded as a fixed experimental condition rather than an optimum compaction pressure. The molded briquettes were carefully removed from the mold and dried before characterization. The briquettes were cylindrical, corresponding to the geometry of the briquette mold used in this study. The exact diameter and height of the produced briquettes were not documented in the available experimental records. Consequently, comparisons related to briquette dimensions could not be performed. The overall experimental procedure consisted of raw-material collection, cleaning, preliminary drying, oven drying, carbonization, grinding, sieving, binder preparation, mixing, compaction, briquette drying, and physicochemical characterization.

Briquette Characterization

The briquettes were characterized in terms of moisture content, ash content, volatile matter, fixed carbon, density, and gross calorific value. The proximate-analysis procedures and calculations were based on mass changes during drying and controlled heating, following the general principles of charcoal characterization (Elder, 2006). Moisture content was expressed on an as-received basis, whereas ash content, volatile matter, and fixed carbon were expressed on a dry basis. The use of a consistent analytical basis was necessary to ensure a valid proximate-analysis mass balance.

Moisture Content

A representative briquette sample was weighed to determine its initial mass. The sample was subsequently dried in an oven at 105°C until a constant mass was obtained. Moisture content was calculated as the percentage of mass lost during oven drying relative to the initial sample mass. The result was reported on an as-received basis. This value represents the amount of moisture present in the briquette under its initial testing condition.

Ash Content

A known mass of the oven-dried briquette sample was placed in a previously weighed porcelain crucible. The sample was heated in a furnace at 900°C for 2 h. After heating, the crucible was cooled and weighed. The ash residue mass was obtained by subtracting the empty crucible mass from the combined mass of the crucible and ash. Ash content was subsequently determined as the percentage of ash residue relative to the initial oven-dried sample mass. The result was expressed on a dry basis. Ash content represents the non-combustible inorganic fraction remaining after the combustible components of the briquette have been oxidized (Yargicoglu *et al.*, 2015).

Volatile Matter

A known mass of the oven-dried briquette sample was placed in a covered crucible and heated under controlled conditions. After heating, the crucible was cooled and weighed. Volatile matter was determined from the reduction in the dry sample mass during heating. The mass loss was expressed as a percentage of the initial oven-dried sample mass. Because the moisture had previously been removed, the result was reported on a dry basis (Yargicoglu *et al.*, 2015).

Fixed Carbon

Fixed carbon was calculated by difference and was not measured directly. On a dry basis, the fixed carbon content was obtained by subtracting the percentages of ash and volatile matter from 100%. Moisture content was not included in this calculation because moisture was reported on an as-received basis, whereas ash, volatile matter, and fixed carbon were reported on a dry basis. Accordingly, the combined percentages of ash, volatile matter, and fixed carbon should equal 100% when all three parameters are expressed on a dry basis (Yargicoglu *et al.*, 2015). If fixed carbon is to be reported on an as-received basis, the ash and volatile matter values must first be converted to the same basis. Fixed carbon can then be determined by subtracting moisture, ash, and volatile matter from 100%. Values expressed on different analytical bases should not be combined in a single calculation.

Briquette Density

Briquette density was determined using the stereometric method. Each briquette was weighed, and its geometric volume was determined from its diameter and height. Density was calculated by dividing the briquette mass by its geometric volume and was reported in g/cm^3 (Rabier *et al.*, 2006). This measurement represents the apparent density of the entire briquette, including its internal pore volume. The stereometric method is appropriate for regularly shaped cylindrical briquettes. However, dimensional irregularities may increase the uncertainty of the calculated density (Rabier *et al.*, 2006).

Gross Calorific Value

The gross calorific value of each briquette formulation was determined using a bomb calorimeter. A known mass of the briquette sample was placed inside the calorimetric vessel and completely combusted under an oxygen atmosphere. The calorimeter was calibrated before sample analysis. Benzoic acid is commonly used as a reference material for calibrating bomb calorimeters (Martinka *et al.*, 2018). The heat released from the sample was determined from the corrected temperature increase of the calorimetric system. Corrections for the ignition wire, ignition thread, acid formation, and other applicable contributions were included when required by the instrument procedure. When the bomb calorimeter automatically calculated the gross calorific value, the calibrated instrument-generated value was recorded. The results were expressed in cal/g. For comparison with studies reporting SI units, values in cal/g may be converted to MJ/kg by multiplying them by 0.004184 (Martinka *et al.*, 2018).

Data Analysis

The moisture content, ash content, volatile matter, fixed carbon, density, and gross calorific value of the four briquette formulations were compared descriptively to evaluate differences associated with binder type. The measured briquette properties were also compared with the charcoal-briquette quality requirements specified in Indonesian National Standard SNI 01-6235-

2000(Berkelanjutan *et al.*, 2020). A formulation was described as having the best performance only when its overall properties were superior within the range of formulations investigated. This comparison did not establish a global optimum beyond the experimental conditions used in the study. Because the number of independent experimental replicates was not documented in the available draft, no inferential statistical analysis was specified. Because independent experimental replicates were not documented, the results were analyzed descriptively, and no inferential statistical analysis was performed.

RESULTS AND DISCUSSION

Overall Characteristics of the Briquettes

The coconut-shell and spent-coffee-ground briquettes produced using four different binders were evaluated in terms of moisture content, ash content, volatile matter, fixed carbon, apparent density, and gross calorific value. These parameters collectively describe the storage stability, inorganic residue, combustion behavior, physical compactness, and energy content of densified biomass fuels (Kpalo *et al.*, 2020; Ibitoye *et al.*, 2021; Obi, Pecenka and Clifford, 2022). The measured properties of the four briquette formulations are summarized in Table 3. The requirements of SNI 01-6235-2000 were included for the parameters that are explicitly regulated by the Indonesian charcoal-briquette standard (Martinka *et al.*, 2018).

Table 3. Fuel characteristics of briquettes prepared using different binders

Parameter	Tapioca starch	Corn starch	PVA	Gohsenx Z-200	SNI 01-6235-2000
Moisture content (%)	6.85	6.60	7.13	6.85	≤8
Ash content (%)	0.91	0.79	1.76	1.00	≤8
Volatile matter (%)	0.87	0.83	0.79	0.92	≤15
Fixed carbon, dry basis (%)	98.22	98.38	97.45	98.08	≥77
Apparent density (g/cm³)	1.22	1.09	1.04	1.00	Not specified
Gross calorific value (cal/g)	6314	6271	6298	6159	≥5000
Gross calorific value (MJ/kg)	26.42	26.24	26.35	25.77	≥20.92

All formulations satisfied the SNI limits for moisture content, ash content, volatile matter, and gross calorific value based on the reported measurements. The reported fixed-carbon values also exceeded the minimum requirement, although their mass-balance consistency must be verified. Apparent density was evaluated as an important physical property but was not compared with SNI 01-6235-2000 because a density requirement is not explicitly stated in the standard. The results also demonstrate that binder selection did not produce the same performance ranking for every parameter. Tapioca starch produced the highest observed apparent density and calorific value, whereas corn starch produced the lowest moisture and ash contents. The moisture contents of the briquettes are presented in Figure 1.

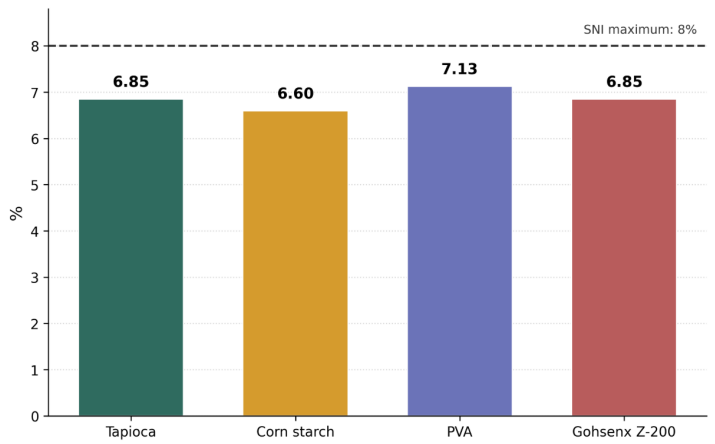


Figure 1. Moisture contents of coconut-shell and spent-coffee-ground briquettes prepared using different binders. The dashed line indicates the maximum value specified by SNI 01-6235-2000.

The moisture content ranged from 6.60 to 7.13%. The corn-starch formulation produced the lowest observed value at 6.60%. The tapioca-starch and Gohsenx Z-200 formulations both produced

a moisture content of 6.85%, whereas the PVA formulation produced the highest value at 7.13%. Nevertheless, all four formulations remained below the maximum SNI limit of 8% (Martinka *et al.*, 2018). Moisture content is an important fuel-quality parameter because part of the energy released during combustion is consumed to evaporate water. Excessive moisture may delay ignition, reduce effective thermal output, and negatively affect briquette storage stability (Kpalo *et al.*, 2020; Ibitoye *et al.*, 2021). Studies involving spent-coffee-ground fuels have similarly identified drying and moisture control as important factors influencing their combustion performance (Brunerová *et al.*, 2019; Espuelas *et al.*, 2020; Jeníček *et al.*, 2022).

The difference between the highest and lowest values was only 0.53 percentage points. The slightly higher moisture content of the PVA formulation may be associated with water retention by its hydrophilic functional groups. However, this explanation remains tentative because the water-absorption behavior of the individual binders and the drying history of the briquettes were not independently evaluated. Binder type, binder concentration, drying conditions, and storage humidity can jointly influence the final moisture content (Obi, Pecenka and Clifford, 2022; Butler, Skrivan and Lotfi, 2023). Because the number of replicates and measurement variability were not reported, the observed differences cannot be considered statistically significant. Therefore, the appropriate interpretation is that corn starch produced the lowest observed moisture content under the experimental conditions.

Ash Content

The ash contents of the four briquette formulations are shown in Figure 2.

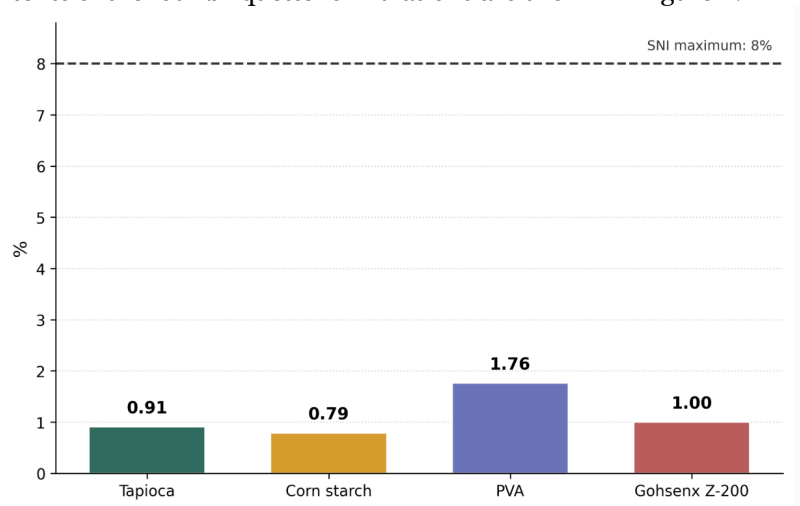


Figure 2. Ash contents of coconut-shell and spent-coffee-ground briquettes prepared using different binders. The dashed line indicates the maximum value specified by SNI 01-6235-2000.

Ash content ranged from 0.79 to 1.76%. The corn-starch formulation produced the lowest ash content at 0.79%, followed by tapioca starch at 0.91%, Gohsenx Z-200 at 1.00%, and PVA at 1.76%. All formulations had ash contents substantially below the maximum SNI requirement of 8% [19]. Ash is the non-combustible inorganic residue remaining after the combustible components have been oxidized. High ash content is undesirable because it does not contribute to energy generation and may increase residue accumulation in combustion equipment [1,2]. Previous studies have demonstrated that briquette ash content may be affected by the mineral composition of the biomass, contamination during processing, carbonization conditions, and the type and quantity of binder (Seetapong *et al.*, 2024; Ramadhana *et al.*, 2025).

The PVA formulation produced approximately twice the ash content of the corn-starch formulation. However, this observation does not demonstrate that PVA inherently contained more inorganic matter. Such a mechanism would require direct ash analysis of the individual binders. Differences could also originate from feedstock heterogeneity, sample preparation, crucible handling, or measurement uncertainty. Therefore, although all formulations satisfied the SNI requirement, replicate analysis is needed to confirm whether binder type produced a reproducible difference in ash content.

Volatile Matter

The volatile-matter contents of the briquettes are presented in Figure 3.

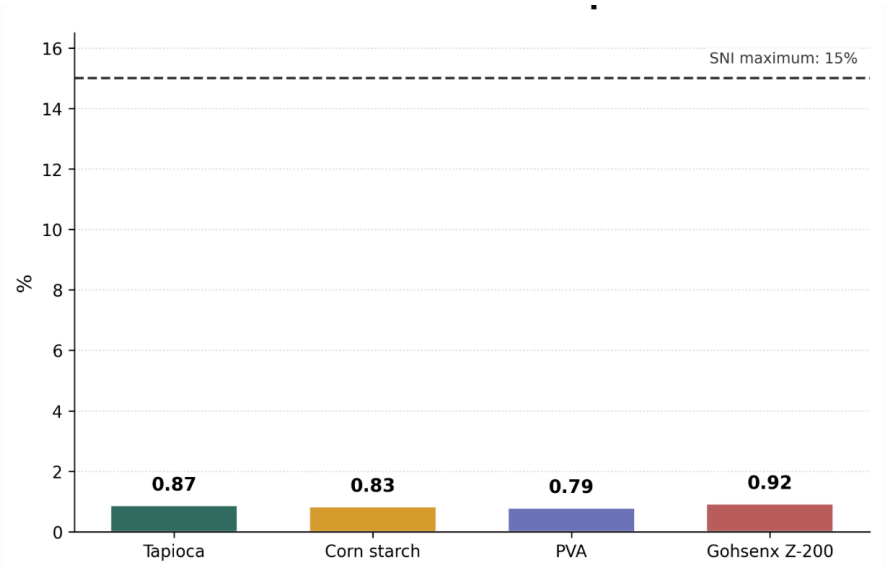


Figure 3. Volatile-matter contents of coconut-shell and spent-coffee-ground briquettes prepared using different binders. The dashed line indicates the maximum value specified by SNI 01-6235-2000.

The reported volatile-matter contents ranged from 0.79 to 0.92%. The PVA formulation produced the lowest value at 0.79%, followed by corn starch at 0.83%, tapioca starch at 0.87%, and Gohsenx Z-200 at 0.92%. All reported values were below the maximum SNI limit of 15% (Martinka *et al.*, 2018). Volatile matter represents compounds released as gases and vapors when a fuel is heated under specified analytical conditions. This fraction influences ignition, flame formation, smoke generation, and the transition from devolatilization to char combustion (Kpalo *et al.*, 2020; Ibitoye *et al.*, 2021). Carbonization generally reduces volatile matter by removing thermally labile biomass components and increasing the relative proportion of carbon-rich solids (Ibitoye *et al.*, 2021).

The reported volatile-matter contents of 0.79–0.92% are unusually low for biomass-derived charcoal briquettes, particularly for materials carbonized at 400°C. Previous studies involving spent coffee grounds and other biomass briquettes generally reported higher volatile-matter contents, although the measured values depend strongly on the analytical procedure and carbonization conditions (Brunerová et al., 2019; Jeníček et al., 2022). If confirmed, such low volatile-matter contents may make initial ignition more difficult, reduce flame propagation during the early combustion stage, and shift the combustion process toward slower oxidation of the fixed-carbon fraction. Low volatile matter may also reduce the formation of smoke and volatile combustion products. However, ignition time, flame propagation, combustion rate, and smoke generation were not directly measured in this study. Moreover, the unusually low values may have been influenced by the sample basis, calculation procedure, heating temperature, heating duration, crucible sealing, or recorded sample masses. Therefore, the original weighing records and analytical procedure should be verified before these values are used to draw definitive conclusions regarding combustion behavior (Brunerová *et al.*, 2019) (Brunerová *et al.*, 2019; Jeníček *et al.*, 2022).

Fixed Carbon

The reported fixed-carbon contents are shown in Figure 4.

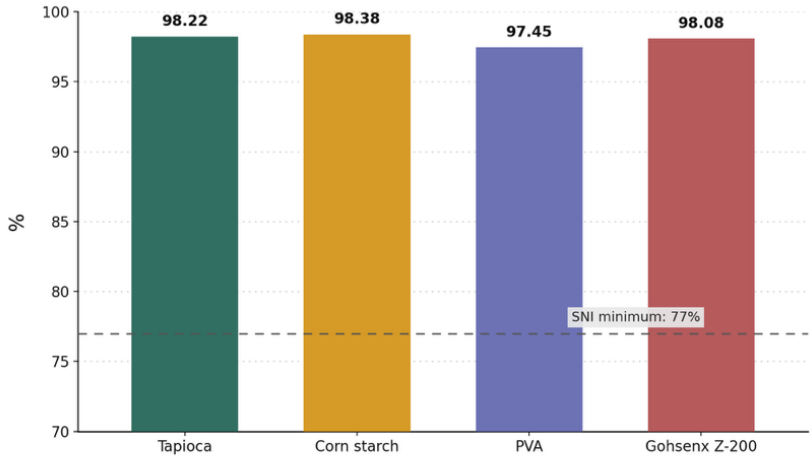


Figure 4. Fixed-carbon contents of coconut-shell and spent-coffee-ground briquettes prepared using different binders, calculated by difference on a dry basis. The dashed line indicates the minimum value specified by SNI 01-6235-2000 (Brunerová *et al.*, 2019; Jeníček *et al.*, 2022).

The fixed-carbon contents calculated by difference on a dry basis ranged from 97.45 to 98.38%. Corn starch produced the highest calculated value of 98.38%, followed by tapioca starch at 98.22%, Gohsenx Z-200 at 98.08%, and PVA at 97.45%. All formulations exceeded the minimum requirement of 77% specified in SNI 01-6235-2000. Fixed carbon was calculated by subtracting the dry-basis ash and volatile-matter contents from 100%. Moisture content was not included because it was reported on an as-received basis. The corrected calculation therefore maintains a consistent analytical basis and produces a valid dry-basis mass balance. Nevertheless, because independent experimental replicates were not documented, the differences among binder formulations should be interpreted descriptively (Brunerová *et al.*, 2019; Ibitoye *et al.*, 2021).

Apparent Density

The apparent densities of the briquettes are presented in Figure 5.

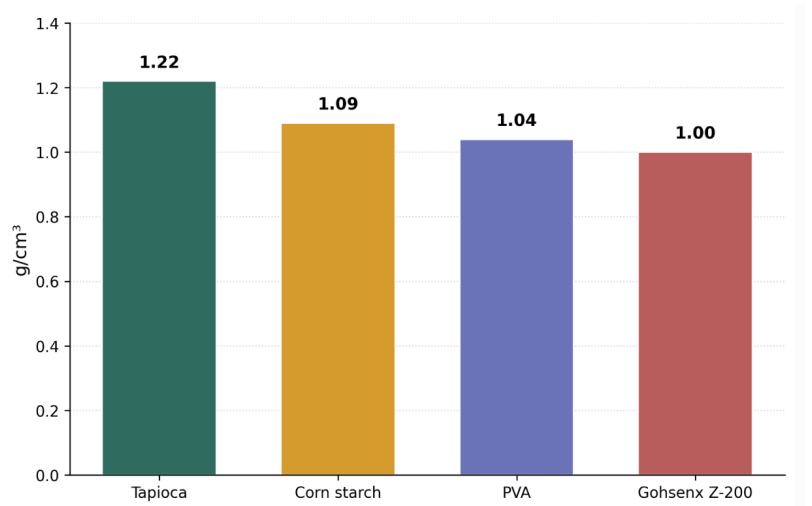


Figure 5. Apparent densities of coconut-shell and spent-coffee-ground briquettes prepared using different binders. No density threshold was assigned because this parameter is not explicitly specified in SNI 01-6235-2000.

Apparent density ranged from 1.00 to 1.22 g/cm³. Tapioca starch produced the highest observed density at 1.22 g/cm³, followed by corn starch at 1.09 g/cm³, PVA at 1.04 g/cm³, and Gohsenx Z-200 at 1.00 g/cm³. The tapioca-bound briquette was approximately 22% denser than the Gohsenx Z-200 formulation. Briquette density can be affected by particle size, compaction pressure, feedstock

deformability, binder distribution, moisture content, and dimensional recovery after removal from the mold (Kpalo *et al.*, 2020; Obi, Pecenka and Clifford, 2022; Butler, Skrivan and Lotfi, 2023). Higher density generally indicates closer particle contact and lower void volume. This characteristic may improve handling and volumetric energy density, although excessive compaction could restrict air penetration during combustion.

The observed ranking suggests that tapioca starch produced a more compact briquette structure under the applied pressing conditions. Gelatinized starch may form solid bridges between adjacent charcoal particles during drying. Nevertheless, the present study did not evaluate porosity, internal structure, compressive strength, or drop resistance. Therefore, higher density cannot be directly interpreted as greater mechanical strength without additional supporting evidence. The density was determined using a stereometric method based on briquette mass and geometric dimensions. Rabier et al. reported that stereometric measurements are sensitive to dimensional irregularities, whereas displacement-based techniques may provide greater reproducibility for irregularly shaped briquettes (Yargicoglu *et al.*, 2015). Replicate measurements of diameter, height, and mass should consequently be reported in future studies.

Gross Calorific Value

The gross calorific values of the four formulations are presented in Figure 6.

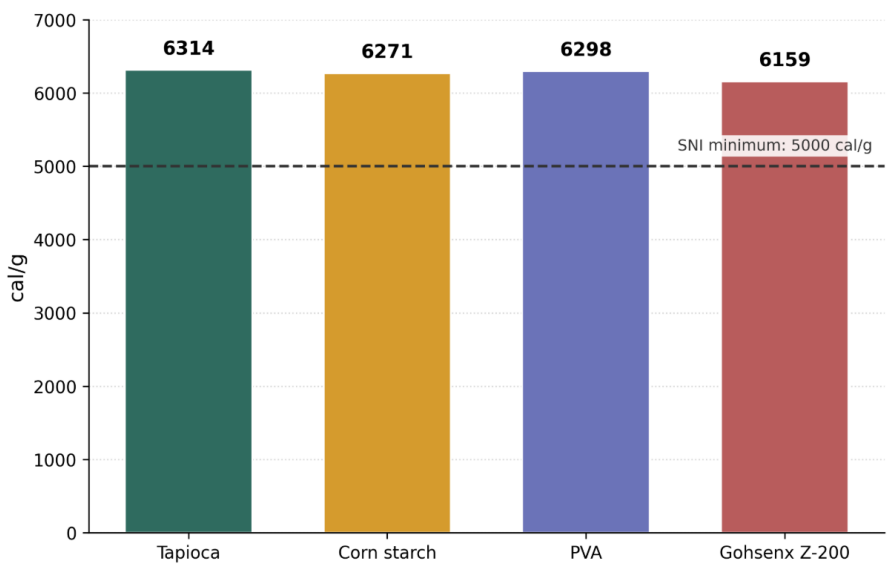


Figure 6. Gross calorific values of coconut-shell and spent-coffee-ground briquettes prepared using different binders. The dashed line indicates the minimum value specified by SNI 01-6235-2000.

The gross calorific values ranged from 6159 to 6314 cal/g, equivalent to approximately 25.77–26.42 MJ/kg. Tapioca starch produced the highest observed value of 6314 cal/g. This was followed by PVA at 6298 cal/g, corn starch at 6271 cal/g, and Gohsenx Z-200 at 6159 cal/g. All formulations exceeded the minimum SNI requirement of 5000 cal/g (Martinka *et al.*, 2018). The measured values are within the energy range reported for densified fuels containing spent coffee grounds and carbonized biomass (Brunerová *et al.*, 2019; Jeníček *et al.*, 2022; Ramadhana *et al.*, 2025). Spent coffee grounds possess substantial energy potential because of their carbonaceous organic constituents and residual lipids, whereas coconut-shell charcoal provides a carbon-rich fraction following carbonization (Brunerová *et al.*, 2019; Jeníček *et al.*, 2022; Ramadhana *et al.*, 2025).

Although tapioca starch produced the highest measured calorific value, its difference from PVA was only 16 cal/g, equivalent to approximately 0.25%. The difference between the highest and lowest formulations was 155 cal/g, or approximately 2.5%. Without replicate bomb-calorimetric measurements and information on measurement uncertainty, these small numerical differences cannot be interpreted as statistically significant. The relatively high calorific value of the tapioca formulation may be associated with its high density, low ash content, and the combustible nature of the starch binder. However, the current data do not demonstrate that carbohydrate content was the dominant mechanism. The influence of a binder on calorific value depends on its energy content, dosage, moisture retention, and ash contribution relative to those of the biomass (Espuelas *et al.*,

2020; Obi, Pecenka and Clifford, 2022; Butler, Skrivan and Lotfi, 2023). Therefore, the defensible conclusion is that tapioca starch produced the highest observed calorific value within the formulations investigated, rather than that it was statistically superior to the other binders.

Overall Comparison of Binder Performance

No single binder produced the most favorable result for every parameter. Corn starch produced the lowest moisture and ash contents and the highest reported fixed-carbon value. Tapioca starch produced the highest apparent density and calorific value. PVA produced the lowest volatile-matter value but also the highest moisture and ash contents. Gohsenx Z-200 produced the lowest density and calorific value. Binder selection should consequently be based on the intended performance criterion. If gross calorific value is the primary criterion, tapioca starch is the leading formulation within the tested range. If low moisture and ash contents are prioritized, corn starch may be preferable. Reviews of biomass briquette binders similarly emphasize that binder selection involves trade-offs among energy performance, mechanical integrity, moisture resistance, ash generation, material availability, and production cost (Obi, Pecenka and Clifford, 2022; Butler, Skrivan and Lotfi, 2023). The absence of independent replicates, standard deviations, mechanical-strength measurements, combustion-rate data, and ignition tests limits the identification of an overall optimum binder. The current results support the selection of tapioca starch as the formulation with the highest observed calorific value, but they do not establish statistically significant superiority or a global optimum.

CONCLUSIONS

Coconut-shell and spent-coffee-ground briquettes were successfully produced using tapioca starch, corn starch, PVA, and Gohsenx Z-200 as binders. Based on the reported measurements, all four formulations satisfied the requirements of SNI 01-6235-2000 for moisture content, ash content, volatile matter, and gross calorific value. The moisture content ranged from 6.60 to 7.13%, ash content from 0.79 to 1.76%, apparent density from 1.00 to 1.22 g/cm^3, and gross calorific value from 6159 to 6314 cal/g. Tapioca starch produced the highest observed gross calorific value of 6314 cal/g and the highest apparent density of 1.22 g/cm^3. Corn starch produced the lowest moisture content of 6.60% and ash content of 0.79%. Therefore, tapioca starch can be identified as the leading binder within the tested formulations when gross calorific value is used as the primary selection criterion. However, its calorific value differed from that of PVA by only 16 cal/g. Without independent replicates and statistical analysis, this numerical difference cannot be interpreted as statistically significant superiority. The fixed-carbon contents were recalculated on a consistent dry basis, while the unusually low volatile-matter values should still be verified against the original weighing records and analytical procedure before final publication. Further studies should incorporate experimental replication, statistical analysis, mechanical durability, ignition behavior, combustion rate, and emission measurements to establish a more comprehensive assessment of binder performance.

DECLARATION OF GENERATIVE AI

The authors declare that no generative AI or AI-assisted technologies were used in the writing process of this manuscript.

CONFLICTING INTEREST STATEMENT

The author declares that there is no conflict of interest in the publication of this article.

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