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Research Article

Controlled-combustion emission benchmarking of cow-manure–rice-husk–sawdust briquettes as firewood substitutes for traditional salt production

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Abstract

Traditional salt production in coastal Indonesia still relies heavily on firewood, contributing to deforestation pressure, unstable fuel supply, and local air-pollution exposure. This study evaluates multi-feedstock biomass briquettes made from cow manure, rice husk, and sawdust as potential firewood substitutes by assessing their proximate properties and controlled-combustion emissions. Briquettes were prepared using a mixture of 74% cow manure, 5% rice husk, 9% sawdust, 1% tapioca starch, and 11% water, then dried to approximately 12% moisture. Proximate analysis (moisture, ash, volatile matter, and fixed carbon by difference) was conducted following standardized wood/biomass fuel test methods. Flue-gas emissions (SO_2, NO_2, CO, opacity, and O_2) were measured in a controlled combustion chamber (garden incinerator) by an accredited laboratory with triplicate measurements, and results were benchmarked against commonly used local firewood (petai, sentang, rambutan) and published pellet data. The briquettes exhibited 12% moisture (as received) and, on a dry basis, 29% ash, 60% volatile matter, and 11% fixed carbon. Emissions showed very low SO_2 (1.2 mg/Nm^3) and moderate NO_2 (7.4 mg/Nm^3), but comparatively high CO (1,857.6 mg/Nm^3), indicating incomplete combustion under the tested airflow and mixing conditions. Overall, the briquettes offer a clear sulfur-emission advantage over firewood, while combustion-system optimization (air supply and fuel–air mixing) is required to reduce CO and improve combustion completeness for salt-processing applications.

1. Introduction

The increasing demand for thermal energy in rural and small-scale industries continues to place pressure on traditional biomass resources, particularly firewood. In Indonesia's coastal salt-producing regions, firewood remains the dominant fuel used for seawater evaporation [1], contributing to high operational costs, inconsistent heat supply, and increased carbon emissions. The reliance on firewood also accelerates deforestation and threatens the long-term sustainability of salt production systems that depend heavily on steady heat availability [2-3].

In response to these concerns, there has been an increasing emphasis on the adoption of renewable energy alternatives, such as biomass, which play a vital role in mitigating environmental degradation [4-7]. Biomass, in particular, holds substantial promise due to its renewable nature

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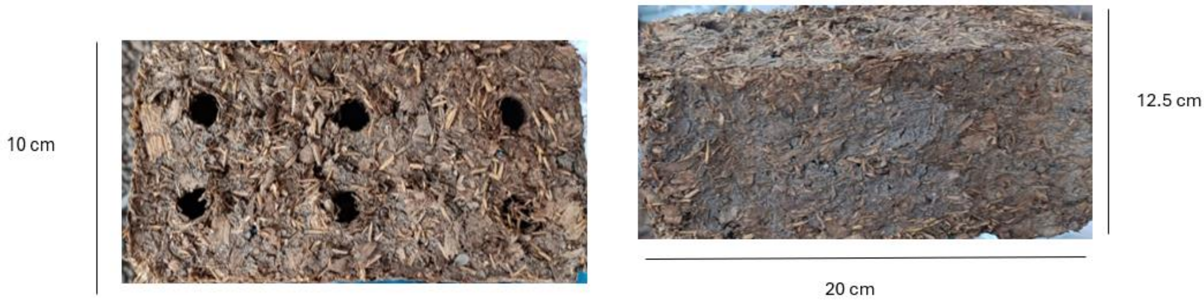
and wide availability from sources such as agricultural residues, livestock waste, and other organic materials [8-12].

The utilization of biomass offers multiple benefits, including the potential for conversion into various alternative fuels [13-15]. Among these, biomass briquettes represent a particularly effective form, produced by compressing organic waste into dense, energy-efficient solid fuels. This conversion improves storage, transportation, and combustion efficiency compared to unprocessed biomass [16-21]. Especially in rural and off-grid communities, biomass briquettes serve as a cost-effective and accessible energy option for everyday activities such as cooking, heating, and small-scale industrial use [22, 23]. Meanwhile, Indonesia generates significant volumes of agricultural and livestock waste—including cattle manure, rice husks, and sawdust—that are often discarded or used inefficiently. These residues hold considerable potential as renewable bioenergy resources when converted into densified bio-briquettes. Biomass briquettes from agricultural have shown promising fuel and combustion properties [24-26]. However, briquette quality and environmental performance vary substantially depending on the mixture, proportion, and physicochemical characteristics of the raw materials.

In our previous study, a briquette product of cow manure, rice husk and wood dust were produced [27]. Figure 1 shows the dimensions of the briquette product, which is 20 cm x 10 cm x 12.5 cm. From the combination of dimensional measurements and mass weighing of briquettes, the average density of dry briquettes is 0.337 gr/cm^3.



(a) (b)

Fig. 1. Geometry and appearance of the produced briquette: (a) top view (left) showing surface perforation holes; (b) side view (right). Nominal dimensions are 20 cm × 10 cm × 12.5 cm (length × width × height)

The utilization of briquettes produced from a mixture of cow manure, rice husk, and wood dust has demonstrated strong performance across several quality assessments. The financial evaluation in our previous study also indicated strong feasibility, with a Net Present Value (NPV) of IDR 144,074,566, an Internal Rate of Return (IRR) of 72.154%, a Net Benefit–Cost ratio (Net B/C) of 4.37, and a payback period of 3.22 years [27]. These indicators collectively show that briquette production is not only technically viable but also financially attractive, while simultaneously offering the potential to reduce dependence on firewood—a major driver of deforestation and environmental degradation in rural communities.

Despite the growing attention to biomass-based solid fuels, research integrating cattle manure, rice husk, and sawdust into a single multi-feedstock briquette remains extremely limited, particularly in the context of coastal salt farming. Existing studies tend to focus on either briquette from a single waste source, household-scale cooking applications, or generalized combustion parameters without examining sector-specific needs. Only limited evidence exists on studies that systematically compare both proximate properties and controlled-combustion emissions of multi-feedstock cow-manure–rice-husk–sawdust briquettes against the firewood types used in traditional salt production systems. This represents a critical gap, given that salt farmers require fuel with stable combustion, low moisture, and reduced pollutants. A representative firewood stockpile commonly used by salt farmers is shown in Figure 2.

Fig. 2. Representative stockpiled firewood commonly used as fuel in traditional coastal salt production (field photograph)

Despite extensive research on agricultural-residue briquettes, evidence remains limited for (i) multi-feedstock briquettes that jointly combine cow manure, rice husk, and sawdust in a single formulation, and (ii) emission benchmarking against the specific firewood types used in traditional salt-processing furnaces. Most prior studies focus on single-feedstock briquettes, household cooking stoves, or general fuel characterization without linking performance to salt-production operational needs (stable heat release, manageable ash handling, and reduced pollutant exposure). Therefore, the scientific contribution of this work is to provide controlled-combustion emission data (SO_2, NO_2, CO, opacity, and O_2) and proximate properties for a locally feasible multi-feedstock briquette formulation, and to directly compare its emission profile with representative tropical hardwood firewood used by salt farmers. The objectives of this study are: (1) to determine moisture, ash, volatile matter, and fixed carbon of the briquettes using standardized proximate-analysis methods; (2) to quantify flue-gas emissions under controlled combustion conditions; and (3) to benchmark briquette emissions against commonly used firewood and published pellet references to assess feasibility as a firewood substitute for traditional salt production.

1.1 Research Questions and Scope

This study addresses three practical research questions: (RQ1) What are the proximate characteristics (moisture, ash, volatile matter, fixed carbon) of the proposed cow-manure–rice-husk–sawdust briquettes under standardized testing? (RQ2) Under controlled combustion conditions, how do the flue-gas emissions (SO_2, NO_2, CO, opacity, and O_2) of the briquettes compare with representative tropical hardwood firewood used by salt farmers? (RQ3) Based on energy-content estimation and emission benchmarking, what is the practical implication for using the briquettes as a partial or full substitute for firewood in traditional salt production?

The scope of the study is limited to controlled combustion tests in a laboratory-type combustion chamber and literature-based benchmarking; field-scale stove trials and long-duration performance tests in operational salt furnaces are recommended as follow-up work.

1.2 Literature Review

Biomass densification into briquettes and pellets has been widely reported as an effective strategy to increase bulk density, improve handling and storage, and stabilize combustion relative to loose residues. Multiple studies show that densified biomass fuels can improve practical usability in rural and small-scale industrial contexts by reducing transport volume and enabling more consistent feeding rates during combustion [16–21,24–26]. However, densification alone does not guarantee cleaner emissions; emission outcomes remain strongly dependent on feedstock composition (e.g., ash-forming minerals and fuel-bound nitrogen) and on combustion conditions (air supply, mixing, and residence time) [14,24,25,35].

Manure- and faecal-based solid fuels have gained attention due to their availability in livestock-dominant regions and their potential to convert sanitation or agricultural residues into usable energy carriers [6,11,12]. Prior studies demonstrate that dung-based briquettes/pellets can be feasible fuels, but they commonly exhibit high ash fractions due to mineral-rich composition, which can increase ash handling requirements and influence combustion stability and residue management [28–30]. In particular, the ash contribution becomes more pronounced when manure is blended with silica-rich residues such as rice husk, potentially affecting both combustion dynamics and post-combustion maintenance [15,18].

Rice husk is frequently highlighted for its availability and its porous structure, which can influence ignition behavior; nevertheless, its high silica content typically elevates ash levels and can pose challenges such as clinker formation or airflow obstruction in certain combustion systems if not managed properly [15,18]. Sawdust and other woody residues, by contrast, often contribute more favorable lignocellulosic combustion characteristics and have been associated with improved briquette strength and stable flaming under appropriate conditions [13,24,25]. Therefore, blending manure, rice husk, and sawdust is technically attractive but requires explicit evaluation of both fuel properties and emission performance due to opposing effects (improved cohesion and availability versus elevated ash and potential incomplete combustion).

Emission performance is a critical criterion for adopting alternative fuels in semi-enclosed work environments such as artisanal processing sites. Studies on pellets and briquettes show that sulfur dioxide (SO_2) can vary widely depending on fuel sulfur content and contamination, while carbon monoxide (CO) is strongly indicative of combustion completeness and is highly sensitive to airflow and mixing conditions [29,35]. Consequently, comparative emission benchmarking against real fuels used in the target application (here, tropical hardwood firewood for salt production) is necessary to assess whether a proposed briquette can realistically reduce pollutant exposure and environmental burden while maintaining sufficient thermal performance.

Although briquette research has grown substantially, evidence remains limited for multi-feedstock formulations that combine cow manure, rice husk, and sawdust in a single blend and, simultaneously, report controlled-combustion emission data benchmarked against the specific firewood types used by traditional salt producers. This limitation motivates the present study, which links proximate properties and controlled emission measurements to the salt-production fuel context.

2. Materials and Methods

2.1 Basic Materials

The basic materials for this research were dried cow dung mixed with rice husks and sawdust. The formulation of Sample was designed to optimize the physical integrity and combustion characteristics of the biomass briquette by utilizing readily available and low-cost organic waste materials. As shown in Table 1, cow dung constitutes the majority of the composition at 74%. This component serves as both a binder and a combustible material, contributing significantly to the fixed carbon content while improving the mechanical cohesion of the briquette due to its fibrous and organic matter content. Cow dung is widely accessible in rural agricultural communities and has been previously recognized for its potential in low-emission biomass fuel production.

Table 1. Raw materials composition

Raw Material	Composition Ratio (%)
Cow Dung	74
Rice Husk	5
Sawdust	9
Tapioca Starch	1
Water	11

2.1.1 Formulation Rationale

The composition in Table 1 was adopted from a prior development and feasibility study of the same briquette product [27] and refined through preliminary mixing trials aimed at achieving (i) sufficient mechanical integrity during molding and drying, and (ii) stable ignition and flame sustainability. Cow manure was set as the dominant fraction because it provides natural binding capacity and structural cohesion, while also contributing combustible organic matter. Rice husk was limited to a low proportion to avoid excessive ash accumulation associated with its high silica content, whereas sawdust was included to increase the carbon-rich fraction and support more stable flaming combustion. Tapioca starch was added as a supplementary binder to improve inter-particle bonding, and water content was adjusted to obtain a workable paste for molding and to activate binder functionality prior to drying.

2.2 Proximate Analysis

Proximate analysis was conducted to determine moisture content, ash, volatile matter, and fixed carbon as key indicators of fuel quality. Moisture content was determined using a standard oven-drying approach for particulate biomass/wood fuels (ASTM E871). Ash content was determined by dry oxidation of the oven-dried sample (ASTM E1755). Volatile matter was determined under standardized high-temperature conditions (ASTM E872). Fixed carbon was calculated by difference as commonly defined in proximate analysis standards (ASTM E870 / ISO 17225-1). Moisture content (as received).

$$MC(\%) = \frac{m_2 - m_3}{m_2 - m_1} \times 100 \tag{1}$$

where $m_1$is the mass of the empty crucible (g), $m_2$is the mass of crucible + wet sample before oven drying (g), and $m_3$is the mass of crucible + sample after oven drying at $103 \pm 2°C$to constant mass (g). Ash content (dry basis).

$$Ash_{db}(\%) = \frac{m_4 - m_1}{m_3 - m_1} \times 100 \tag{2}$$

where $m_1$is the mass of the empty crucible (g), $m_3$is the mass of crucible + oven-dried sample used for ashing (g), and $m_4$is the mass of crucible + ash after oxidation in a muffle furnace (g). Volatile matter (dry basis).

$$VM_{db}(\%) = \frac{m_3 - m_5}{m_3 - m_1} \times 100 \tag{3}$$

where $m_5$is the mass of crucible + residue after volatile-matter determination (g). Fixed carbon (dry basis, by difference).

$$FC_{db}(\%) = 100 - (Ash_{db} + VM_{db}) \tag{4}$$

All reported proximate fractions (Ash_{db}, VM_{db}, FC_{db}) are on a dry basis, while moisture content is reported as received.

2.3 Comparative Analysis

To evaluate the performance of the briquettes, the proximate analysis results were compared with briquettes produced from different biomass feedstocks reported in previous studies and commonly used firewood types sourced from the literature. This comparative approach was used to assess whether the briquettes meet or exceed standard fuel characteristics associated with efficient and clean combustion.

2.4 Emission Analysis

The second stage of the study focused on evaluating the combustion emissions of the multi-feedstock briquettes. The pollutants measured included sulfur dioxide (SO_2), carbon monoxide

(CO), and nitrogen dioxide (NO_2). Emission testing was performed using a Garden Incinerator. A generic emission analyzer was employed to measure gas emission concentrations. The procedures carried out are as follows:

2.4.1 Emission Measurements

During combustion, gaseous emissions from the briquettes and the comparative wood fuels—petai (*Parkia speciosa*), sentang (*Azadirachta excelsa*), and rambutan (*Nephelium lappaceum*)—were quantified using a generic emission analyzer. The measurement procedures adhered to established national testing protocols, with sulfur dioxide (SO_2) assessed following Method Ik.5.04.02.01, carbon monoxide (CO) using Method Ik.5.04.02.03, and nitrogen dioxide (NO_2) using Method Ik.5.04.02.02. Opacity measurements were performed in accordance with SNI 19.7117.11.2005. All analytical methods were implemented in compliance with the emission monitoring requirements outlined in Appendix 1 of the Ministry of Environment and Forestry Regulation No. 11/2021. The testing was carried out by the Industrial Standardization and Service Agency of Banda Aceh (Balai Standardisasi dan Pelayanan Jasa Industri Banda Aceh), ensuring conformity with accredited national standards.

The applied procedures and reporting format follow the emission monitoring framework and definitions in the Ministry of Environment and Forestry Regulation No. 11/2021 and the Indonesian National Standard for opacity testing (SNI 19.7117.11.2005).

2.4.2 Accuracy, Calibration, and Repeatability

All emission measurements in this study were conducted by the Industrial Standardization and Service Agency of Banda Aceh (BSPJI/BARISTAND), following the official Indonesian test methods for stationary combustion sources, namely IK.5.04.02.01 (SO_2), IK.5.04.02.02 (NO_2), and IK.5.04.02.03 (CO). These methods comply with the Ministry of Environment and Forestry Regulation Appendix 1 No. 11 of 2021 on Emission Standards for Combustion. The procedures include mandatory calibration and accuracy verification steps prior to each test. According to IK.5.04.02.03, the emission analyzer undergoes free-air calibration and instrument self-check for approximately 180 seconds to ensure measurement stability and accuracy. Each pollutant measurement is performed in three consecutive repetitions, as required by Section 6.2.3 of the method, with a measurement duration of ten minutes per repetition. This triplicate measurement protocol ensures data repeatability and reduces variability in the reported concentrations. The accuracy, resolution, and detection limits of the analyzer follow the specifications validated by BSPJI through routine certified reference gas calibration, ensuring that the emission data generated in this study meet nationally standardized metrological requirements.

2.4.3 Combustion Testing of Briquettes

Combustion trials were conducted for the briquettes formulated from cow manure, rice husks, and wood dust, alongside comparative tests using petai wood (*Parkia speciosa*), sentang wood (*Azadirachta excelsa*), and rambutan wood (*Nephelium lappaceum*). Each fuel type was burned individually in a Garden Incinerator under controlled conditions.

Controlled combustion tests were conducted using a commercially available garden incinerator operated as a batch, natural-draft combustion chamber. The incinerator body is equipped with multiple air holes (ventilation openings) that function as primary air inlets to supply combustion air to the fuel bed. Flue gas exits through an upper chimney/funnel that promotes draft and directs exhaust upward. Flue-gas sampling was conducted at the chimney/funnel outlet, where the sampling probe was positioned in the exhaust stream to ensure consistent and comparable measurements across fuels. The same sampling location and test configuration were applied for all fuel types.

The tests were performed at an ambient air temperature of 33 ± 1°C, with the measured oxygen concentration in the flue gas approximately 19 ± 1% to ensure consistent combustion environments across all samples. Throughout the combustion process, key gaseous and optical emission parameters—including sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide

(NO_2), oxygen (O_2), and flue-gas opacity—were continuously monitored to characterize the emission profile of each fuel.

2.4.4 Data Analysis

The emission data recorded by the generic emission analyzer for each gas during combustion were analyzed to evaluate the emission levels of the briquettes made from cow manure, rice husks, and wood dust compared to the emissions produced by firewood commonly used by salt farmers under identical testing conditions, and emission data reported in previous studies for other types of briquettes and firewood. This comparative framework enabled a broader assessment of whether the briquettes offer environmental advantages over conventional fuels and other biomass-based alternatives documented in the literature.

2.5 Research Flow Chart

A flow chart is used to visually represent the process or sequence of steps undertaken in this research. It illustrates the procedures, starting from the preparation of equipment and materials to the data analysis phase. The flow chart in this study is as shown in Figure 3.

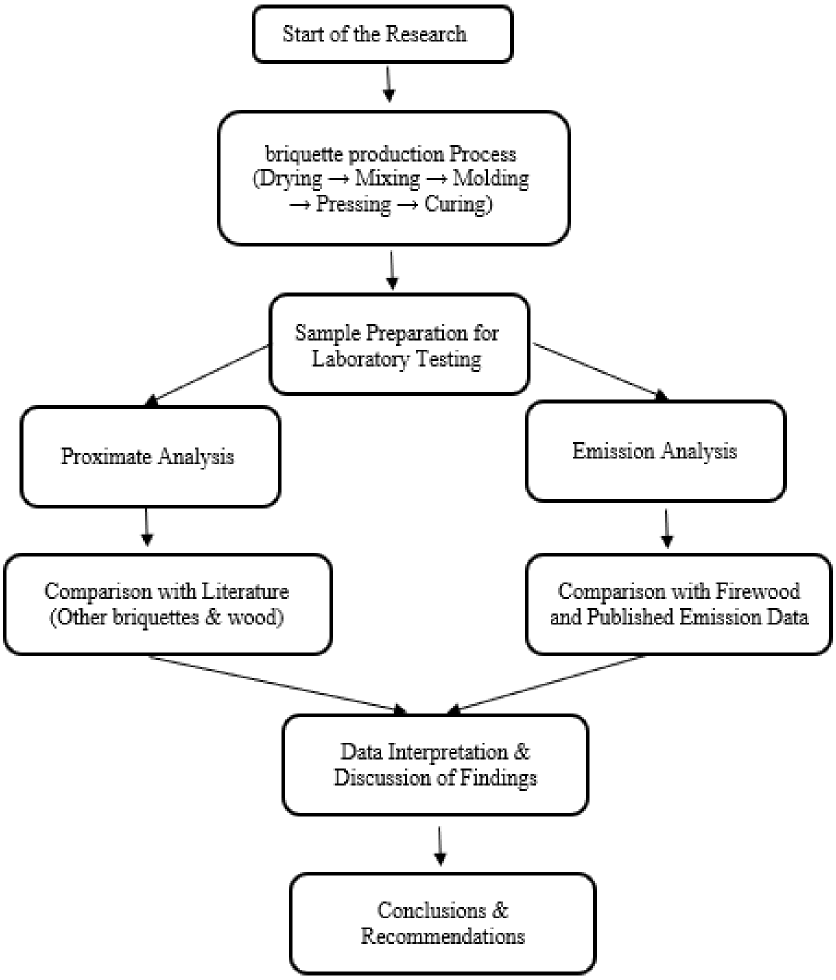


Fig. 3. Research Flow chart

2.6 Conceptual Framework

The analytical framework of this study links feedstock formulation to end-use feasibility through two measurable domains: (i) proximate properties as indicators of ignition behavior, ash handling, and char-burning potential; and (ii) controlled-combustion emissions as indicators of environmental and occupational exposure risks. The briquette formulation (cow manure–rice husk–sawdust) is treated as the primary design variable, proximate fractions (MC, ash, VM, FC) as intermediate fuel-quality descriptors, and emission outputs (SO_2, NO_2, CO, opacity, O_2) as performance indicators. The framework enables benchmarking against firewood used in salt production and against pellet references from the literature to identify advantages (e.g., low SO_2) and constraints (e.g., high CO under limited mixing), thereby informing practical recommendations for combustion-system optimization.

3. Results and Discussion

3.1. Results

3.1.1 Proximate Characteristics of the Produced Briquettes

The proximate analysis revealed distinct combustion-related properties of the briquettes formulated from cow dung (74%), rice husk (5%), sawdust (9%), tapioca starch (1%), and water (11%). The results indicate that the produced briquettes contain 12% moisture, 29% ash, 60% volatile matter, and 11% fixed carbon, positioning them within the general performance profile of non-carbonized biomass briquettes.

Table 2. Comparison of proximate characteristics of cow-dung-based briquettes with previous studies

Parameter (%)	This Study	Cow-dung Briquette [28]	Cow-dung Pellets [29]	Composite Briquette with Cow Dung Binder [30]
Moisture	12.00	6.94	~18	3.16
Ash	29.00	25.47	10–20	3.60
Volatile Matter	60.00	18.58	50–70	80.20
Fixed Carbon	11.00	49.02	~18.61	13.04

When compared with previous studies, the moisture content of the briquettes is higher than the value reported by Rahmaisyanti but lower than the typical moisture levels found in cow-dung pellets reviewed by Szymajda. This moderate moisture level suggests that the briquettes remain suitable for combustion without requiring excessive drying time.

The ash content (29%) is relatively high and closely aligns with the ash level of cow-dung-dominant briquettes (25.47%) in Rahmaisyanti. The elevated ash is consistent with the mineral-rich composition of cow dung and the additional silica contribution from rice husk. Compared with composite briquettes that use cow dung only as a binder, the ash content in this study is substantially higher, reflecting the greater proportion of inorganic residues inherent in the feedstock blend.

Volatile matter of the produced briquettes reached 60%, which is significantly higher than the value reported for cow-dung-only briquettes in Rahmaisyanti but still within the 50–70% range documented by Szymajda. This high volatile fraction indicates that the briquettes ignite easily and burn quickly, which is advantageous for fuel applications requiring fast combustion, such as traditional salt processing.

The fixed carbon content (11%) is lower than reported in the cow-dung-only briquettes of Rahmaisyanti, where fixed carbon reached 49.02%. This discrepancy reflects differences in formulation, as the cow-dung briquettes in prior studies often use carbonized or partially carbonized feedstocks. In contrast, the non-carbonized formulation used in this study—combined with low-fixed-carbon biomass such as rice husk and sawdust—naturally results in lower fixed-carbon content. Nevertheless, the fixed carbon value remains comparable to composite briquettes using cow dung as a binder [30], which reported 13.04%.

3.1.2 Comparison Between Briquette Characteristics and Conventional Firewood

The proximate characteristics of the cow-dung-based briquettes produced in this study were compared with benchmark values for conventional firewood reported in the literature. The briquettes exhibited a moisture content of 12%, which falls within the typical range of 8–15% observed in several fuelwood species such as *Eucalyptus pellita*, *Acacia* spp., mangrove species, and multiple Indonesian hardwoods. This indicates that the drying process of the briquettes is comparable to the standard practices for seasoned firewood, and moisture is unlikely to hinder ignition performance.

Table 3. Typical proximate characteristics of common firewood species (literature benchmarks)

Wood / Source (type)	Moisture (%)	Ash (%)	Volatile matter (%)	Fixed carbon (%)	Source
Eucalyptus pellita (wood) — Indonesia study	10–14	0.8–2.5	70–78	18–25	[31]
Acacia spp. (fuelwood / charcoal feedstock) — tropical study	8–12	0.5–4.0	65–80	15–25	[32]
Ulin / Eusideroxylon (several Indonesian woods — proximate reported)	6–12	0.5–3.0	65–80	15–28	[33]
Mangrove species (wood, multiple species) — charcoal/proximate report	8–15	0.6–3.5	60–78	17–28	[34]

However, a substantial contrast emerges in the ash content. The briquettes contained 29% ash, which is considerably higher than the 0.5–5% range commonly reported for firewood. Studies on *Eucalyptus pellita*, *Acacia* spp., mangrove wood, and Indonesian species such as *Eusideroxylon* consistently show low mineral residue after combustion. In comparison, the briquettes' ash content is an order of magnitude higher. This difference reflects the intrinsic mineral composition of cow dung and the contribution of rice husk silica, which together elevate inorganic content. Consequently, the briquettes are expected to produce more post-combustion residue than firewood, a factor that may affect stove maintenance and ash disposal requirements.

In terms of volatile matter, the briquettes recorded 60%, which aligns with the reported values for firewood, typically ranging between 60–80%. This suggests that the briquettes, like natural biomass, contain a substantial proportion of easily combustible components that support rapid ignition and flame formation in the early combustion stage. Meanwhile, the fixed carbon content of the briquettes (11%) is lower than the 15–28% typical of hardwood fuel. Because fixed carbon governs the duration of the glowing-phase combustion, firewood is expected to burn longer and retain embers more effectively compared to the briquettes. These differences collectively indicate that the briquettes may ignite readily but may not sustain long-lasting heat without frequent fueling.

31.3. Emission Performance

The emission characteristics of the cow manure–rice husk–wood dust briquette was compared with three local wood fuels (Petai, Sentang, Rambutan) and two reference fuels from the literature (cow dung pellets and woody pellets). The results are summarized in Table 4.

Table 4. Comparison of research results with other briquettes with cow manure base material

No.	Test Parameters	Cow manure, rice husk, and wood dust	Petai wood	Sentang wood	Rambutan Wood	Cow Dung Pellets [29]	Woody Pellets [35]
1	SO_2 (mg/Nm^3)	1.2	75.4	7.6	94.4	244.38	2.68
2	NO_2 (mg/Nm^3)	7.4	3.6	12.8	4.6	-	-
3	CO (mg/Nm^3)	1,857.6	1,643.8	1,502.4	1,568.2	854.77	329.87
4	Opacity (%)	20	20	20	20	-	-
5	Oxygen (O_2 %)	18.9	19.53	18.72	19.39	11.59	9.14

3.1.4 Sulfur Dioxide (SO_2)

The briquette produced a very low SO_2 concentration of 1.2 mg/Nm^3, substantially lower than Petai (75.4 mg/Nm^3) and Rambutan (94.4 mg/Nm^3), and also lower than the high-SO_2 cow dung pellets reported in the literature (244.38 mg/Nm^3). Its SO_2 value was comparable to woody pellets (2.68 mg/Nm^3), indicating that the sulfur content of the briquette's raw materials is inherently low. This suggests that the mixture of cow manure, rice husk, and sawdust does not introduce significant sulfur-bearing compounds and thereby minimizes the potential for acidifying emissions.

3.1.5 Nitrogen Dioxide (NO_2)

The briquette emitted 7.4 mg/Nm^3 of NO_2, a value within the range observed for the three wood species (3.6–12.8 mg/Nm^3). Although reference values for NO_2 from cow dung pellets and woody pellets were not available, the data indicate that the fuel blend produces nitrogen oxides at levels comparable to conventional wood combustion. This suggests that fuel nitrogen content in the briquette is moderate and does not significantly elevate NOx formation during combustion.

3.1.6 Carbon Monoxide (CO)

Measured CO concentration for the cow manure–rice husk–wood dust briquette was 1,857.6 mg/Nm^3, which reference fuels: Petai (1,643.8 mg/Nm^3), Sentang (1,502.4 mg/Nm^3), Rambutan (1,568.2 mg/Nm^3), cow-dung pellets from literature (854.77 mg/Nm^3), and woody pellets (329.87 mg/Nm^3). The markedly elevated CO emissions indicate a high degree of incomplete combustion for the briquette under the applied test conditions.

Overall, Table 4 indicates a clear trade-off profile: the briquettes provide a strong SO_2 reduction benefit relative to the tested firewood types, while CO levels suggest incomplete oxidation under the present airflow/mixing conditions. This trade-off is consistent with the expectation that dense, heterogeneous fuels with high volatile release require adequate secondary air and mixing to complete volatile oxidation, especially in natural-draft chambers.

3.2 Discussion

The proximate analysis (Table 2) provides the fuel-quality context required to interpret the emission trends (Table 4) and to assess practical feasibility for traditional salt boiling. Overall, the produced briquettes represent a non-carbonized dung–agro-residue fuel characterized by moderate moisture (12% as received) and a volatile-rich composition (VM = 60% on a dry basis), accompanied by a high ash burden (Ash = 29% db) and relatively low fixed carbon (FC = 11% db). These attributes are broadly consistent with reported variability of cow-dung-based solid fuels, where moisture and proximate fractions are strongly influenced by feedstock composition, drying practice, and densification conditions [28–29].

Moisture plays a key role in ignition behavior and effective heat release because part of the fuel energy is consumed to heat and evaporate water before stable combustion is achieved. The 12% moisture content measured here is higher than the 6.94% reported by Rahmaisyanti et al. [28], yet lower than the ~18% moisture level reported for cow-dung pellets in Szymajda et al. [29]. This difference is plausibly associated with differences in pre-drying intensity and with the present formulation process, where 11% water was added to activate binder functionality and improve molding consistency prior to drying. Importantly, 12% remains within the typical operational range reported for non-carbonized biomass briquettes and should not prevent practical handling and ignition under appropriate firing conditions [25,29].

Ash content and operational implication. A major distinguishing characteristic of the studied briquettes is the high ash fraction (29% db). This value is comparable to the 25.47% ash content reported for cow-feces/coffee-ground briquettes by Rahmaisyanti et al. [28], supporting the interpretation that elevated ash is a feedstock-driven feature of dung-dominant formulations rather than a production defect. For end-use applications, high ash implies increased residue management and a higher likelihood of airflow obstruction if ash accumulates in the primary-air zone. Therefore, ash handling and grate/airflow design become more critical when deploying these briquettes in salt-production furnaces than when using low-ash hardwood firewood (Table 3).

Volatile matter and fixed carbon balance. The briquettes exhibit VM = 60% db, which falls within the broad range commonly reported for non-carbonized biomass briquettes and is consistent with the "volatile-rich" character of many dung-based fuels reviewed by Szymajda et al. [29]. In contrast, Rahmaisyanti et al. reported substantially lower VM (18.58%) and higher FC (49.02%) for briquettes where processing choices and material composition favored a more char-like behavior [28]. The present briquettes show FC = 11% db, closer to the lower fixed-carbon regime expected for non-carbonized blends and comparable to other residue-briquette reports (e.g., FC ~13% in Geberehiet et al.) [30]. Practically, this VM–FC balance suggests rapid initial flaming (good for quick heat establishment) but a shorter ember/char phase than fuels with higher fixed carbon, potentially requiring more frequent refueling during long salt-boiling cycles.

Taken together, the proximate profile confirms that the developed briquettes fall within expected ranges for non-carbonized dung–residue fuels [28–30] and provides a mechanistic basis for interpreting the emission outcomes in Table 4, particularly the trade-off between very low SO_2 and elevated CO under the tested natural-draft combustion configuration.

3.2.1 Suitability of the Briquettes for Thermal Applications

Based on the proximate profile (Table 2), the briquettes exhibit characteristics compatible with practical is the highest value among all fuels tested in this study and substantially exceeds the CO reported for the thermal uses that require reliable ignition and sustained heating, including traditional salt boiling. The moderate as-received moisture (12%) together with a volatile-rich dry-basis composition (VM = 60%) indicates that the fuel can ignite readily and establish a stable flame when adequate air supply is available, consistent with general briquette combustion behavior reported for agro-residue and dung-derived solid fuels [25,29]. At the same time, the high ash fraction (Ash = 29%)—likely influenced by mineral-rich manure and silica-bearing rice husk—implies that residue management and maintaining airflow through the fuel bed will be more critical than for low-ash hardwood firewood [15,25]. The relatively low fixed carbon (FC = 11%) also suggests a shorter ember/char phase than many hardwood fuels, so long salt-boiling cycles may require more frequent feeding or operational adjustments to maintain consistent heat output [25,29].

3.2.2 Implications of Differences in Fuel Properties for End-Use Performance

Compared with the firewood benchmarks (Table 3), the briquettes are expected to offer comparable ignition convenience under similar moisture conditions, but with distinct operational requirements. The substantially higher ash content implies more frequent ash removal and a higher risk of airflow restriction if ash accumulates in the primary-air zone; therefore, end-use feasibility for salt boiling depends not only on fuel availability but also on the ability of the furnace/stove configuration to maintain airflow despite ash generation (e.g., through periodic cleaning and appropriate ash handling) [25]. In addition, the lower fixed carbon fraction indicates shorter burn endurance per unit mass than many hardwood fuels, which can be accommodated through feeding schedules already typical in artisanal boiling processes, but should be recognized as a key difference affecting heat maintenance behavior [25,29]. These property-driven implications provide the practical context for interpreting the emission trade-offs discussed in the next subsection (Table 4).

3.2.3 Mechanistic Interpretation and Implications of Emission Performance

The contrasting emission behaviors observed among the tested fuels highlight the complex interplay between feedstock composition, physicochemical properties, and combustion dynamics. The extremely low SO_2 emissions from the cow-manure–rice-husk–wood-dust briquette can be attributed to its inherently low sulfur content. Rice husk contributes a high proportion of silica and negligible sulfur, while cow manure contains sulfur predominantly in organic forms that decompose without substantial SO_2 release. This composition-driven advantage positions the briquette as a cleaner alternative to sulfur-bearing hardwoods, which consistently exhibited higher SO_2 concentrations. From an environmental standpoint, the exceptionally low sulfur footprint is critical for mitigating acid gas formation and aligning with stringent emission thresholds adopted in clean-energy policies.

The moderate NO_2 emission level reflects both the nitrogen composition of cow manure and the combustion temperature profile. Manure-based fuels tend to generate some fuel-NOx due to nitrogenous biochemical residues. However, the low to moderate flame temperature typical of manure–biomass blends inhibit thermal-NOx formation, which explains why NO_2 concentrations remained far below those commonly associated with herbaceous biomass. This reduced NOx formation enhances the suitability of the briquette for small-scale thermal applications where ventilation is limited and NO_2 exposure becomes a functional health concern. Compared to woody biomass that tends to burn at higher temperatures, the briquette's-controlled combustion temperature indirectly benefits nitrogen emission control.

The most striking behavior is the elevated CO emissions relative to all comparison fuels, including pelletized cow dung and woody pellets. Mechanistically, this is likely influenced by a combination of structural and combustion factors: (i) higher briquette density limiting internal air diffusion, (ii) heterogeneity of its organic–inorganic matrix affecting heat transfer, and (iii) partial devolatilization of manure components generating combustible gases that are not fully oxidized. Pelletized fuels, by contrast, are mechanically densified under precisely controlled parameters, ensuring uniform ignition, stable temperature rise, and enhanced mixing of oxygen with volatile gases—conditions that facilitate more complete oxidation and thereby reduce CO significantly. The findings highlight the need for improvements in briquette formulation, such as optimizing particle size, pressing force, and binder ratios to enhance porosity and combustion stability.

In the broader context of thermal energy development, these results demonstrate that while the briquette delivers significant environmental benefits in terms of SO_2 and NO_2 suppression, optimization is essential to meet desirable CO emission standards. Nonetheless, the emission patterns observed indicate strong potential for deployment in rural or small-industry applications, provided that burning technologies are adapted to improve combustion completeness. The briquette's low-sulfur and low-NOx characteristics may contribute to cleaner air and reduced exposure risk for traditional salt producers and households relying on biomass fuels.

3.2.4 Study Limitations and Implications for Interpretation

The combustion tests were conducted in a garden-incinerator chamber as a controlled and repeatable setup; however, this configuration does not fully replicate the airflow pattern, heat transfer, and fuel-feeding practice of traditional salt-production furnaces. Consequently, the absolute CO concentrations reported here should be interpreted as chamber-specific indicators of combustion completeness rather than direct field-equivalent values. Future work should include (i) field trials in representative salt furnaces, (ii) tests under controlled excess-air ratios and secondary-air staging, and (iii) reporting of oxygen-corrected concentrations to a defined reference O_2 level where required by the target standard.

3.3 Energy Requirement Implication for Salt Boiling (Illustrative Estimation)

In addition to emission benchmarking, an energy-demand context is useful for judging feasibility of the proposed briquettes for traditional salt boiling. Because direct calorific value testing (e.g., bomb calorimetry) was not performed in this study, the briquette higher heating value (HHV) was estimated from proximate analysis using the correlation by Parikh et al. [36]. The correlation expresses HHV on a dry basis as:

$$HHVdb\ (MJ/kg) = 0.3536 \cdot FC + 0.1559 \cdot VM - 0.0078 \cdot Ash \tag{5}$$

where FC, VM, and Ash are wt% on a dry basis. Using the measured proximate fractions of the briquettes (Table 2: FC = 11%, VM = 60%, Ash = 29%), the estimated HHV is ≈ 13.02 MJ/kg (dry basis). With 12% moisture as received, a first-order as-received estimate is ≈ 11.46 MJ/kg briquette (13.02 × 0.88).

For salt boiling, the dominant theoretical energy requirement is water evaporation from brine. As a simple illustration, evaporating 1 kg of water typically requires on the order of ~2.5 MJ (heating from ambient to boiling plus latent heat). If brine entering the boiling step is concentrated to 20% salt, producing 1 kg salt requires evaporating approximately ~4 kg water, corresponding to ~10

MJ/kg salt of theoretical heat demand. In practice, actual fuel consumption will be higher due to heat losses and combustion completeness (consistent with the elevated CO observed in Table 4); therefore, improving airflow management and mixing (secondary air) is expected to increase useful heat release and reduce the required briquette mass during salt boiling.

The increasing utilization of waste biomass (including rice husk and sawdust) as an engineered feedstock has been driven by both waste-management needs and concerns over deforestation, supporting the rationale for converting locally available residues into solid fuels [37]. Beyond technical performance, adoption among salt farmers is strongly influenced by institutional and socio-economic factors. A recent logistic regression study among salt farmers in rural Aceh indicates that policy support, perceived economic feasibility, and environmental awareness are the strongest predictors of willingness to adopt cattle-manure briquettes [38]. Therefore, technical improvements (e.g., CO reduction through better air supply and mixing) should be complemented by implementation strategies that address these adoption drivers.

4. Conclusions

This study assessed multi-feedstock biomass briquettes produced from cow manure, rice husk, and wood dust as potential substitutes for tropical hardwood firewood used in traditional salt production. The work combined proximate analysis with controlled-combustion emission testing and benchmarking against commonly used local firewood (petai, sentang, rambutan) and pellet references from the literature. The proximate analysis indicates that the briquettes represent a non-carbonized biomass fuel with 12% moisture (as received) and a dry-basis composition of 29% ash, 60% volatile matter, and 11% fixed carbon. These characteristics imply easy ignition and rapid volatile-driven flaming but a comparatively limited char-burning phase relative to many hardwood fuels. The high ash fraction is an inherent consequence of mineral-rich manure and silica-bearing rice husk, and it signals a practical requirement for more frequent ash removal and furnace/grate designs that avoid airflow blockage during long boiling operations.

Emission measurements show a distinctive environmental profile. The briquettes produced exceptionally low SO_2 concentrations (1.2 mg/Nm^3), substantially lower than all tested firewood types and lower than the cow- dung pellet reference, indicating a strong sulfur-emission advantage for reducing acid gas formation and potential corrosion/irritation risks in work environments. NO_2 emissions (7.4 mg/Nm^3) were within the range observed for the tested woods, suggesting that the fuel blend does not elevate NOx to atypical levels under the applied conditions. In contrast, CO emissions were the highest among the compared fuels (1,857.6 mg/Nm^3), indicating incomplete combustion in the present chamber configuration. This outcome is consistent with the need for improved oxygen delivery and mixing (e.g., staged/secondary air) when burning dense heterogeneous briquettes with high volatile release under natural-draft conditions.

From a feasibility standpoint, the briquettes provide a clear emission benefit with respect to sulfur, while their practical deployment for salt production should be accompanied by operational adaptation and combustion-system optimization. Recommendations include: (i) improving furnace or stove airflow management (primary and secondary air pathways), (ii) adjusting briquette geometry/porosity or densification parameters to enhance internal diffusion and stable burning, and (iii) implementing ash management practices suitable for high-ash fuels. The present study is limited to controlled combustion in a garden-incinerator chamber; therefore, field trials in representative salt furnaces, reporting of oxygen-corrected emissions where required, and direct calorific value measurement (bomb calorimetry) are recommended to refine energy-demand estimates and strengthen deployment guidance. Overall, the briquettes show strong potential as a locally sourced, renewable fuel alternative that can reduce firewood dependency, provided that combustion design is improved to lower CO and increase thermal efficiency.

From a broader sustainability perspective, aligning material and energy choices with climate and environmental targets requires a lifecycle-conscious approach and policy-aware decision making, reinforcing the motivation to evaluate alternative fuels beyond purely technical performance [39].

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