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Original Research Article

Optimizing Corn-Starch–Bonded Palm Shell Biochar Briquettes for Circular Bioenergy Applications

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ABSTRACT

Rapid expansion of palm oil cultivation in Southeast Asia has generated substantial volumes of palm shell residues that remain underutilized within circular production systems. Although briquetting technologies offer promising waste-to-energy pathways, empirical evidence regarding the performance implications of bio-based starch binders under decentralized manufacturing conditions remains limited. This study investigates the production of palm shell biochar briquettes using corn starch as a natural adhesive and evaluates how varying binder proportions influence moisture content, ash content, burning rate, and peak burning temperature relative to Indonesian National Standards. Four formulations with constant charcoal mass and systematically varied starch dosages were fabricated through batch carbonization, grinding, sieving, molding, and solar drying, followed by standardized fuel-quality testing. The results demonstrate that starch dosage exerts a non-linear influence on briquette performance: low binder levels promoted high combustion temperatures and reduced moisture but were associated with elevated ash contents, whereas high starch additions minimized ash formation at the expense of increased moisture retention and reduced thermal output. Among the tested formulations, the 60 g starch mixture provided the most balanced overall performance and the strongest conformity with regulatory thresholds. These findings confirm the technical feasibility of starch-bonded palm shell briquettes as renewable solid fuels and underscore the importance of formulation optimization for circular bioenergy deployment in palm-producing regions. The study offers practical guidance for small-scale producers and contributes to broader efforts to integrate agricultural-residue valorization into localized circular-economy systems.

***Keywords**: palm shell waste; biochar briquettes; circular bioenergy; starch binder; agricultural residues; renewable solid fuel.*

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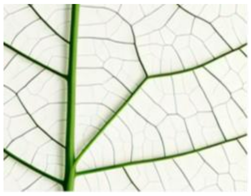
INTRODUCTION

The transition toward sustainable resource use and low-carbon energy systems has intensified global interest in circular economy strategies that retain material value, minimize waste generation, and substitute fossil-based energy carriers with renewable alternatives (Geissdoerfer et al., 2017; Ghisellini et al., 2016; Kirchherr et al., 2017). Within agro-industrial regions, agricultural residues represent a particularly important yet underutilized resource stream, often disposed of through open dumping or low-efficiency combustion practices that generate environmental pollution and forego opportunities for value creation (Scarlat et al., 2015). The palm oil industry exemplifies this challenge. Alongside crude palm oil production, large volumes of lignocellulosic by-products—including empty fruit bunches, fibers, and palm shells—are generated annually, frequently exceeding local reuse capacities and placing pressure on waste-management systems (Lam et al., 2018; Sulaiman et al., 2011). Although palm shells possess high calorific potential, they remain insufficiently integrated into formal energy supply chains, especially in rural contexts where decentralized circular production systems could play a transformative role.

Solid biofuels such as charcoal briquettes have emerged as promising vectors for converting dispersed biomass residues into transportable, energy-dense products suitable for household cooking, small-scale industries, and off-grid energy systems. Briquetting densifies loose biomass, improves combustion stability, and facilitates standardized quality control, thereby addressing logistical barriers that often constrain direct residue utilization (Kaliyan & Morey, 2009). In circular economy terms, such waste-to-energy pathways exemplify closed-loop material strategies in which industrial by-products are reintegrated into productive cycles rather than discarded (Kirchherr et al., 2017). Recent policy initiatives across Southeast Asia have further emphasized the need to strengthen renewable energy deployment while simultaneously reducing environmental pressures associated with agro-industrial waste accumulation, enhancing rural energy access, and diversifying income sources (IEA Bioenergy, 2018). However, the technical viability and performance optimization of residue-based briquettes remain critical prerequisites for large-scale adoption.

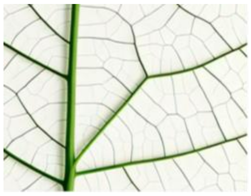
Among the various biomass residues produced by palm oil processing, palm shells are distinguished by their relatively high fixed-carbon content, low volatile matter compared with fibrous residues, and structural density, making them particularly suitable for charcoal production (Lam et al., 2018). Through controlled carbonization, palm shells can be transformed into biochar with favorable combustion characteristics (Basu, 2018). Nevertheless, the subsequent briquetting stage introduces new technical challenges, most notably the selection and dosage of suitable binders that ensure mechanical integrity without compromising thermal efficiency or increasing ash formation (Kaliyan & Morey, 2010). Conventional briquette binders include molasses, clay, synthetic resins, and starch-based adhesives, each associated with distinct environmental footprints, cost structures, and combustion behaviors (Demirbas, 2009). From a circular systems perspective, bio-based binders derived from renewable feedstocks are increasingly preferred because they complement the sustainability credentials of biomass fuels and avoid introducing fossil-derived additives into renewable energy products.



Corn starch constitutes one of the most widely accessible natural binders for charcoal briquettes due to its adhesive properties when gelatinized in water, low toxicity, biodegradability, and availability within agricultural supply chains (Kaliyan & Morey, 2010). Its application is particularly attractive for small-scale producers and rural enterprises seeking low-cost, locally sourced inputs. Despite these advantages, starch binders can also influence briquette performance by altering moisture retention, ignition behavior, burning rate, and ash residue (Demirbas, 2009). Excessive binder content may reduce calorific value or hinder air diffusion during combustion, whereas insufficient binder levels can compromise structural durability during handling and transport. Determining optimal starch proportions is therefore essential for balancing mechanical stability and fuel efficiency in circular bioenergy applications.

Previous research on palm-based briquettes has largely concentrated on feedstock selection, carbonization temperature, particle size distribution, and comparative calorific performance among different agricultural residues (Lam et al., 2018; Sulaiman et al., 2011). While several studies acknowledge the importance of binders, systematic experimental evaluation of binder ratios—particularly under decentralized laboratory or workshop conditions—remains relatively limited. Indonesian studies have also explored decentralized carbonization technologies for nut-shell biomass, including the development of vertical multi-chamber candlenut shell reactors that operate without external fuel inputs (Amri et al., 2019; Darma & Amri, 2019). Subsequent investigations quantified ash content and charcoal yield from these systems, demonstrating compliance with Indonesian National Standards and highlighting the sensitivity of product quality to chamber temperature profiles (Amri et al., 2021a; Amri et al., 2021b). Moreover, many investigations emphasize calorific value as the primary performance indicator, with less attention devoted to comprehensive quality metrics such as moisture content, ash yield, burning rate, and peak burning temperature relative to established fuel standards. These parameters are critical for ensuring that waste-derived briquettes meet regulatory requirements, perform reliably in household stoves, and gain acceptance among end users. However, systematic evaluation of binder ratios—particularly starch-based adhesives—under workshop-scale conditions remains limited.

Within the Indonesian context, the Indonesian National Standard (Standar Nasional Indonesia, SNI) for charcoal briquettes provides benchmark thresholds for moisture and ash content intended to safeguard fuel quality and combustion efficiency. Aligning waste-derived briquettes with such standards is a crucial step toward market entry and institutional uptake, particularly if circular bioenergy initiatives are to be integrated into regional development programs and renewable energy policies. Yet empirical studies explicitly linking binder optimization strategies with SNI compliance for palm shell briquettes remain scarce, especially those conducted in peripheral palm-producing districts where infrastructure constraints and small-scale production dominate.



Against this backdrop, the present study investigates the production of palm shell biochar briquettes bonded with corn starch and evaluates how varying binder proportions affect key fuel performance indicators, including moisture content, ash content, burning rate, and maximum burning temperature. The experimental work was undertaken in Aceh Selatan, Indonesia, a region characterized by active palm oil cultivation and growing interest in

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resource-efficient waste management practices within technical training institutions. By situating the investigation within a workshop-scale laboratory environment, the study reflects realistic decentralized production conditions commonly envisioned in circular economy and industrial-symbiosis models that emphasize localized waste valorization (Boons et al., 2017; Chertow, 2007).

This article makes three principal contributions to scholarship on circular bioenergy and sustainable solid fuels. First, it provides empirical evidence regarding the influence of starch binder dosage on palm shell briquette quality, extending existing biomass briquetting research beyond feedstock-centric analyses. Second, it benchmarks experimental briquettes against national quality standards, thereby linking laboratory optimization with regulatory compliance and market readiness. Third, it frames palm shell briquetting as a localized circular economy strategy capable of transforming agro-industrial residues into renewable energy carriers within rural production ecosystems.

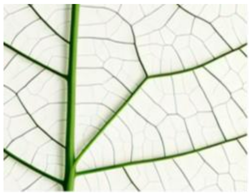
The remainder of the article is organized as follows. The next section reviews relevant literature on circular bioeconomy frameworks, biomass briquetting technologies, binder effects in solid biofuels, and palm oil residue valorization, culminating in the formulation of research propositions guiding the experimental investigation. Subsequent sections describe the research methodology, present the experimental results, and discuss their implications for circular energy systems, decentralized manufacturing models, and sustainable rural development. The article concludes by summarizing the main findings, outlining limitations, and identifying directions for future research on scaling, life-cycle impacts, and policy integration of residue-based briquette production.

LITERATURE REVIEW

2.1 Circular Bioeconomy and Agricultural Residue Valorization

Circular economy frameworks emphasize maintaining the value of materials and energy through closed-loop systems, waste prevention, and cascading resource use across industrial networks (Kirchherr et al., 2017). Within agro-industrial contexts, these principles underpin the concept of a circular bioeconomy, wherein biological resources and residues are converted into renewable energy carriers, biochemicals, and bio-based materials (D'Amato et al., 2017; Scarlat et al., 2015). Agricultural residues—including husks, shells, stalks, and processing by-products—have been identified as critical feedstocks for such systems because they are produced in large volumes, geographically dispersed, and often associated with environmental management challenges when left untreated.

In palm oil–producing regions, residue valorization has attracted increasing policy and research attention due to the sector's environmental footprint and the growing demand for renewable energy alternatives. Studies emphasize that converting palm residues into solid biofuels can reduce methane emissions from unmanaged decomposition, substitute for fossil fuels in rural energy supply, and generate supplementary income streams for smallholders and cooperatives (Lam et al., 2018; Sulaiman et al., 2011). Nevertheless, circular bioenergy initiatives face technical and institutional barriers, including inconsistent feedstock quality,



lack of standardized production protocols, and limited integration with regulatory frameworks governing fuel quality and emissions.

The broader literature on circular construction and industrial ecology further reinforces the relevance of localized waste-to-energy systems. Industrial symbiosis models illustrate how by-products from one production process can become valuable inputs for another, thereby reducing overall system-level environmental burdens and strengthening regional resource resilience (Boons et al., 2017; Chertow, 2007). Within this perspective, palm shell briquetting represents a micro-scale example of industrial symbiosis linking agricultural processing facilities with decentralized energy production units.

2.2 Palm Oil Residues and Energy Recovery Pathways

Palm oil processing generates a diverse portfolio of lignocellulosic residues, including empty fruit bunches, mesocarp fibers, palm kernel shells, and palm shells, each exhibiting distinct physical and chemical characteristics relevant to energy conversion (Lam et al., 2018). Among these, palm shells are often highlighted for their relatively high fixed-carbon content, low ash fraction compared with fibrous residues, and dense structure, which collectively favor charcoal production and high-energy-density fuels (Sulaiman et al., 2011). Thermochemical conversion pathways for palm residues include direct combustion, carbonization, gasification, and pyrolysis, with briquetting commonly employed as a post-treatment step to improve fuel uniformity and handling (Antal & Gronli, 2003; Basu, 2018).

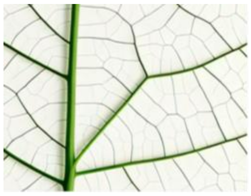
Comparative studies consistently report superior calorific values for shell-derived char relative to fibrous residues, though these advantages depend strongly on optimized residence times, heating rates, and carbonization temperatures (Basu, 2018). Insufficient control of such parameters may increase volatile matter or ash formation, undermining fuel quality and end-user acceptance

Empirical studies comparing different palm residues consistently report superior calorific values for shell-derived char relative to empty fruit bunch–based products, supporting the selection of palm shells as feedstocks for premium solid biofuels. However, these advantages are contingent upon particle size distributions, optimized residence times, heating rates, and carbonization temperatures (Basu, 2018). Inadequate control over these parameters can lead to high volatile content, excessive ash formation, or poor briquette durability, underscoring the importance of integrated process optimization across the entire briquetting chain.

While much of the palm-residue energy literature focuses on feedstock selection and thermal conversion efficiency, comparatively less attention has been devoted to the densification stage, particularly the role of binders in shaping mechanical integrity and combustion behavior. This omission is notable given that binder choice and dosage directly affect briquette durability during transport, ignition stability, and compliance with quality standards.

2.3 Biomass Briquetting Technologies and Quality Standards

Biomass briquetting is widely recognized as an effective densification technology that converts loose, heterogeneous residues into standardized solid fuels with improved bulk density, reduced moisture variability, and enhanced transportability (Kaliyan & Morey, 2009).



Mechanical piston presses, screw extruders, and roller presses are among the most commonly deployed briquetting technologies, each characterized by different pressure regimes and energy requirements (Tumuluru et al., 2011).

Quality assessment of briquettes typically encompasses proximate analysis (moisture, ash, volatile matter, and fixed carbon), calorific value, compressive strength, drop resistance, ignition time, and burning rate. International and national standards—including those developed by ISO and country-specific agencies such as Indonesia's SNI—provide benchmark thresholds intended to ensure consumer safety, stove compatibility, and energy efficiency. Compliance with such standards is increasingly regarded as essential for commercial viability and institutional adoption of waste-derived fuels. Indonesia's SNI (2000) stipulates the minimum parameters that briquettes must have, as stated in SNI 1-6235-2000, as shown in Table 1.

Table 1. Minimum briquette quality parameters based on SNI 1-6235-2000

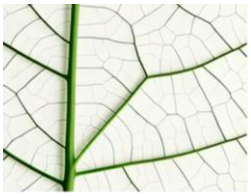
No.	Type of test	Unit	Quality Requirement
1	Moisture content	%	Max. 8
2	The mass loss at 90°C	%	Max. 15
3	Ash content	%	Max. 8
4	Calorific value	Kal/gr	Min. 5000

However, many small-scale or community-based briquette producers operate outside formal certification systems, relying instead on empirical trial-and-error approaches to mixture design. This gap between laboratory optimization and regulatory compliance represents a critical challenge for scaling circular bioenergy solutions in rural settings. Studies, therefore, call for greater integration of standards-based testing protocols into experimental research on agricultural-residue briquettes, particularly when targeting policy-relevant applications.

2.4 Binder Effects in Solid Biofuels

Binders play a central role in briquette production by promoting particle cohesion and structural integrity during compaction, storage, and transport (Kaliyan & Morey, 2010). Common binder materials include molasses, clay, lignin-rich residues, paper pulp, synthetic resins, and starch-based adhesives derived from maize or cassava (Demirbas, 2009). Each binder type influences briquette properties differently, affecting not only mechanical strength but also moisture retention, ash formation, volatile release, and combustion temperature.

Natural starch binders are particularly attractive in decentralized production systems due to their low toxicity, biodegradability, and compatibility with agricultural supply chains (Mani et al., 2006; Tumuluru et al., 2011). When gelatinized in water, starch forms viscous pastes capable of coating char particles and creating cohesive networks upon drying (Kaliyan & Morey, 2010). Nevertheless, excessive starch content can increase moisture uptake, reduce effective carbon concentration, and elevate ash yields, thereby diminishing fuel efficiency. Conversely, insufficient binder proportions may result in fragile briquettes prone to breakage during handling and transport (Demirbas, 2009).



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Empirical investigations across various biomass feedstocks consistently emphasize the existence of optimal binder windows in which mechanical durability and combustion performance are jointly maximized (Kaliyan & Morey, 2010). Such studies demonstrate that binder optimization is highly feedstock-specific, depending on particle size, char porosity, and surface chemistry. Despite these insights, systematic evaluation of starch binder ratios for palm shell briquettes under decentralized production conditions remains limited, representing a notable research gap addressed by the present study.

2.5 Research Gap and Propositions

The foregoing review highlights several unresolved issues within the literature on circular bioenergy and biomass briquetting. First, although palm shells have been widely recognized as promising feedstocks for solid biofuels, comparatively few studies have focused on binder optimization strategies aligned with regulatory quality standards (Lam et al., 2018; Kaliyan & Morey, 2010). Second, while starch-based adhesives are commonly used in practice, their dosage-dependent effects on ash content, moisture retention, burning rate, and peak burning temperature remain underexplored for palm shell–derived char. Third, much of the existing work emphasizes centralized or industrial-scale briquetting systems, with limited attention to workshop-scale or community-based production contexts that are central to circular economy transitions in rural regions.

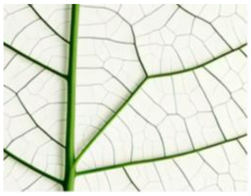
To address these gaps, the present study advances an experimental investigation of palm shell biochar briquettes bonded with corn starch under laboratory conditions representative of decentralized manufacturing environments. Guided by circular bioeconomy principles and solid-fuel quality frameworks, the research evaluates how systematic variation in binder proportion influences compliance with Indonesian National Standards and key combustion performance indicators.

Accordingly, the research design and analytical approach are anchored in three foundational propositions. First, reducing starch binder content within palm shell briquettes improves combustion performance by lowering ash content and enhancing burning stability. Second, there exists an optimal starch dosage that balances mechanical cohesion with thermal efficiency in palm shell biochar briquettes. Finally, binder-optimized palm shell briquettes can serve as technically viable renewable fuels within localized circular bioenergy systems. Collectively, these propositions serve as the guiding hypotheses, directly informing the experimental methodology and subsequent data analysis.

METHOD

3.1 Research Design

This study adopted an experimental laboratory-based design to evaluate the production of palm shell biochar briquettes bonded with corn starch and to determine how binder dosage influences fuel quality within a circular bioenergy framework. A parametric mixture approach was employed, in which four briquette formulations were fabricated with a constant charcoal mass and systematically varied starch content. This approach has been widely applied in



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biomass densification experimental research, such as studies done by Kaliyan & Morey (2010) and Tumuluru et al. (2011). This design enabled controlled assessment of the effects of binder proportion on moisture content, ash content, burning rate, and peak burning temperature—key indicators of solid biofuel performance for household and small-scale industrial applications.

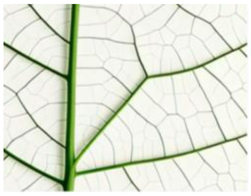
The experimental program was conducted at a Material Testing Laboratory in Politeknik Aceh Selatan and the Kinematics & Catalysis Laboratory of the Chemical Engineering Department, Syiah Kuala University, Indonesia. It is located within a palm-producing region characterized by significant agro-industrial residue generation. By situating the study within a workshop-scale environment rather than a fully industrialized plant, the research reflects decentralized production conditions commonly envisioned in circular economy and industrial-symbiosis models that emphasize localized waste valorization and community-based energy systems (Boons et al., 2017; Chertow, 2007).

3.2 Materials and Data Sources

3.2.1 Palm Shell Feedstock

Palm shells were collected from local palm-oil processing activities in Aceh Selatan, Indonesia, a region characterized by continuous throughput of fresh fruit bunches and correspondingly steady generation of solid residues. In industrial practice, palm shells—often referred to as palm kernel shells—are known for their dense and hard structure, relatively low moisture after natural weathering, and favorable fuel characteristics compared with fibrous residues such as empty fruit bunches (Lam et al., 2018; Sulaiman et al., 2011). Previous proximate and ultimate analyses reported in the literature indicate that palm shells typically contain high fixed-carbon fractions (20–30 %), moderate volatile matter, and comparatively low ash contents (generally <5 %), alongside elemental compositions dominated by carbon (≈45–55 %) and oxygen with smaller proportions of hydrogen and nitrogen (Abdullah & Wu, 2009; Lam et al., 2018). These properties underpin their frequent selection as premium feedstocks for charcoal, biochar, and densified solid fuels.

Prior to carbonization, the shells in the present study were air-dried under ambient conditions to reduce free moisture and to approximate preprocessing practices commonly available to small-scale or community-based producers, rather than industrial kiln drying. Visible contaminants such as adhering soil particles, residual mesocarp fibers, and stones were manually removed to ensure feedstock homogeneity and to avoid artificial inflation of ash content during subsequent combustion tests, in line with recommendations from biomass-fuel characterization studies (Kaliyan & Morey, 2009; Lam et al., 2018). Although the shells were not subjected to full laboratory-scale chemical characterization before carbonization, their selection was guided by extensive regional and international evidence demonstrating that palm shells exhibit superior energy density and char yield relative to other palm-oil residues when processed via slow pyrolysis or carbonization routes (Sulaiman et al., 2011; Basu, 2018). Collectively, these attributes justify the use of palm shells as the primary feedstock in this study and support their positioning within circular bioenergy systems aimed at upgrading agro-industrial by-products into renewable solid fuels.



3.2.2 Carbonization Process

Dried palm shells were converted into charcoal through batch carbonization using a metal-drum kiln equipped with vertically stacked chambers, following decentralized reactor concepts previously developed for nut-shell biomass conversion (Amri et al. 2019; Darma & Amri, 2019). The shells were heated under a limited oxygen supply until volatile gases were largely expelled and a stable char matrix was formed. After cooling, the charcoal was manually crushed and sieved to obtain relatively uniform particle sizes suitable for briquetting.

Temperature control and residence times were monitored during carbonization to ensure consistency with earlier studies demonstrating that chamber-level thermal gradients significantly influence charcoal yield and ash formation (Amri et al., 2021a; Amri et al., 2021b). The use of low-technology reactors mirrors realistic rural conversion systems and supports the study's circular-bioenergy orientation.

3.2.3 Binder Preparation

Corn starch was used as the sole binding agent. The starch was mixed with water and heated until gelatinization occurred, producing a viscous paste capable of coating char particles and promoting cohesion during compaction. This preparation method was selected because of its simplicity, low cost, compatibility with decentralized briquette manufacturing systems, and consistency with established biomass-briquetting practice, in which starch forms solid bridges between particles upon drying and cooling (Kaliyan & Morey, 2010; Mani et al., 2006).

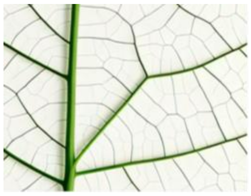
3.2.4 Briquette Formulations

Four briquette formulations were prepared by combining 100 g of palm shell charcoal with varying starch masses: 20 g, 40 g, 60 g, and 100 g. The starch paste was gradually blended into the charcoal until a homogeneous mixture was achieved. The wet mixture was subsequently placed into cylindrical molds and compacted manually using a plunger to form uniform briquettes. The four briquette formulations are presented in Table 1.

Table 2. Four samples of briquette formulations.

Sample	Palm shell charcoal (g)	Starch (g)
S1	100	20
S2	100	40
S3	100	60
S4	100	100

The selected dosage range was informed by prior densification research indicating that binder proportion strongly influences mechanical integrity and combustion behavior, and that excessive binder contents may dilute fixed-carbon fractions or elevate ash yields (Demirbas, 2009; Tumuluru et al., 2011).



3.3 Drying Procedure

Freshly molded briquettes were removed from the molds and subjected to solar drying for several days until mass stabilization indicated sufficient moisture removal. Drying under ambient conditions was chosen to reflect realistic rural production scenarios in which access to controlled ovens or industrial dryers may be limited. Final moisture content was measured after drying to ensure comparability across formulations.

3.4 Performance Testing

Briquette quality was evaluated through moisture content, ash content, burning rate, and peak burning temperature measurements, consistent with international and Indonesian fuel-testing frameworks for solid biofuels (International Organization for Standardization, 2014; Indonesian National Standard, 2000). Each formulation was tested in triplicate to ensure repeatability and statistical robustness. Four primary performance indicators were measured using the following equation:

1. ***Moisture content*** was quantified via gravimetric analysis, whereby the sample mass loss upon heating is measured. This entails oven-drying at a controlled temperature (typically 105 ± 5°C) to a constant mass, ensuring complete evaporation of free and adsorbed water. Mathematically written as:

$$\textbf{Moisture content }(\%) = \frac{\boldsymbol{Initial\ weight - Final\ weight}}{\boldsymbol{Initial\ weight}} \times \mathbf{100}\%$$

2. ***Ash content*** was quantified by combusting dried samples in a muffle furnace at 600 °C and expressing residual mass as a percentage of dry sample weight. It can be written mathematically as follows:

$$\textbf{Ash content }(\%) = \frac{\boldsymbol{Weight\ of\ residual\ ash}}{\boldsymbol{Initial\ weight\ of\ sample}} \times \mathbf{100}\%$$

3. ***Burning rate*** was calculated from mass-loss measurements over time during controlled combustion tests in a laboratory stove.

$$\boldsymbol{Burning\ rate} \ = \frac{\boldsymbol{Initial\ mass - Final\ mass}}{\boldsymbol{Total\ combustion\ time}} \times \mathbf{100}\%$$

4. ***Maximum burning temperature***, measured using a thermocouple positioned above the briquette surface during combustion.

3.5 Data Analysis

Experimental data were analyzed descriptively and comparatively across the four starch dosages. Mean values and standard deviations were calculated for each performance parameter to identify trends associated with binder proportion. Results were subsequently compared with threshold values specified in Indonesian National Standards to evaluate regulatory compliance and practical suitability for domestic fuel applications.

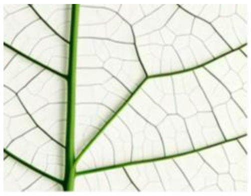


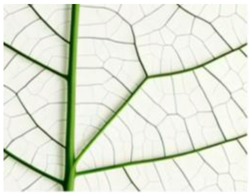
Figure 2. Research processes flowchart

RESULT

4.1 Overview of Experimental Outcomes

Four palm shell biochar briquette formulations were successfully produced using constant charcoal mass and varying corn-starch binder contents (20 g, 40 g, 60 g, and 100 g per 100 g charcoal). All briquettes maintained structural integrity after molding and solar drying, although visible differences in surface texture and density were observed across formulations. reflecting starch-induced variations in particle bonding and pore development reported in biomass-densification studies (Kaliyan & Morey, 2010; Tumuluru et al., 2011).

Performance evaluation focused on moisture content, ash content, burning rate, and maximum burning temperature, consistent with Indonesian National Standard (SNI) testing protocols for charcoal briquettes. Mean values for each indicator are reported in Table 6.



4.2 Moisture Content

Measured moisture contents are presented in Table 3. An increasing trend was observed with rising starch dosage. Briquettes containing 20 g and 40 g of starch exhibited similar and relatively low moisture levels (5.67% and 5.77%, respectively). A further increase was recorded for the 60 g formulation (6.84%), while the 100 g starch briquettes showed the highest residual moisture content at 9.74%. Such patterns are consistent with earlier work demonstrating that starch binders increase hygroscopicity and moisture retention in densified biomass fuels when applied at elevated proportions (Demirbas, 2009; Kaliyan & Morey, 2010). Based on SNI thresholds for charcoal briquettes, the formulations containing 20 g, 40 g, and 60 g starch satisfied moisture requirements, whereas the 100 g formulation exceeded the prescribed limit (Indonesian National Standard, 2000).

Table 3. Moisture content performance

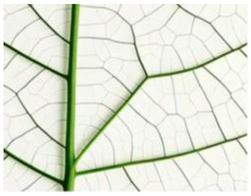
Sampel	Palm shell charcoal (g)	Starch (g)	Moisture content
S1	100	20	5.67%
S2	100	40	5.77%
S3	100	60	6.84%
S4	100	100	9.74%

4.3 Ash Content

Table 4 summarizes ash content results. Considerable variation was observed among formulations. Briquettes containing 40 g starch recorded the highest ash content (10.71%), followed by the 20 g formulation (10%). The 60 g starch briquettes exhibited intermediate ash levels (7.5%), while the lowest ash content was measured for the 100 g starch formulation (5%). These trends are consistent with densification studies reporting that binder dosage modifies mineral dilution effects and post-combustion residue formation in charcoal briquettes (Kaliyan & Morey, 2010; Tumuluru et al., 2011). Accordingly, only the 60 g and 100 g formulations clearly satisfied the SNI requirement, whereas the 20 g and 40 g formulations exceeded or approached the regulatory limit (Indonesian National Standard, 2000).

Table 4. Ash content performance

Sampel	Initial weight (g)	Weight of residual ash (g)	Ash content
S1	147	14.7	10%
S2	133	14.23	10.71%
S3	109	8.18	7.5%
S4	176	8.8	5%



4.4 Burning rate

Burning-rate performance and associated temperature measurements are presented in Table 5. All samples displayed identical ignition times of two minutes; however, burning durations and calculated mass-loss rates differed substantially. The fastest burning rate was observed for the 40 g starch formulation (0.0260 g/s), followed by the 100 g briquettes (0.0200 g/s). Lower rates were recorded for the 20 g formulation (0.0186 g/s), while the slowest burning behavior occurred in the 60 g briquettes (0.0142 g/s). Such variation accords with theoretical and experimental evidence that binder-induced changes in briquette porosity and permeability strongly influence oxygen diffusion and combustion kinetics (Kaliyan & Morey, 2009; Tumuluru et al., 2011).

Table 5. Burning rate performance

Sampel	Ignition time (minutes)	Burning time (minutes)	Burning rate (gr/s)	Temperature (°C)
S1	2	129	0.0186	430
S2	2	80	0.0260	425
S3	2	130	0.0142	429.5
S4	2	158	0.0200	400

4.5 Maximum Burning Temperature

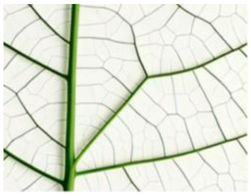
Peak burning temperature measurements indicated that starch dosage influenced thermal output. The highest maximum temperatures were recorded for the 20 g starch formulation (430 °C), followed by progressively lower peaks for the 60 g (429.5 °C) and 40 g (425 °C) briquettes. The 100 g starch samples exhibited the lowest peak temperatures (400 °C). These outcomes correspond with thermochemical theory linking reduced fixed-carbon fractions and increased ash dilution to depressed flame temperatures (Antal & Gronli, 2003; Basu, 2018). Replicate measurements exhibited limited dispersion, indicating stable thermal behavior under the applied test conditions.

4.6 Summary of Briquette Performance

Table 6 summarizes the palm shell briquette performance across starch binder dosages and is visualized in Figure 2.

Table 6. Summary of palm shell briquette performance across starch binder dosages.

Starch content (g/100 g charcoal)	Moisture content (%)	Ash content (%)	Burning rate (g/s)	Max temperature (°C)
S1 (20 g)	5.67 (Lowest)	10 (Higher)	0.0186 (Faster)	430 (Highest)
S2 (40 g)	5.77 (Moderate)	10.71 (Highest)	0.0260 g/s (Slowest)	425 (Moderate)
S3 (60 g)	6.84 (Higher)	7.5 (Moderate)	0.0142 g/s (Fastest)	429.5 (Higher)
S4 (100 g)	9.74 (Highest)	5 (Lowest)	0.0200 g/s (Moderate)	400 (Lowest)



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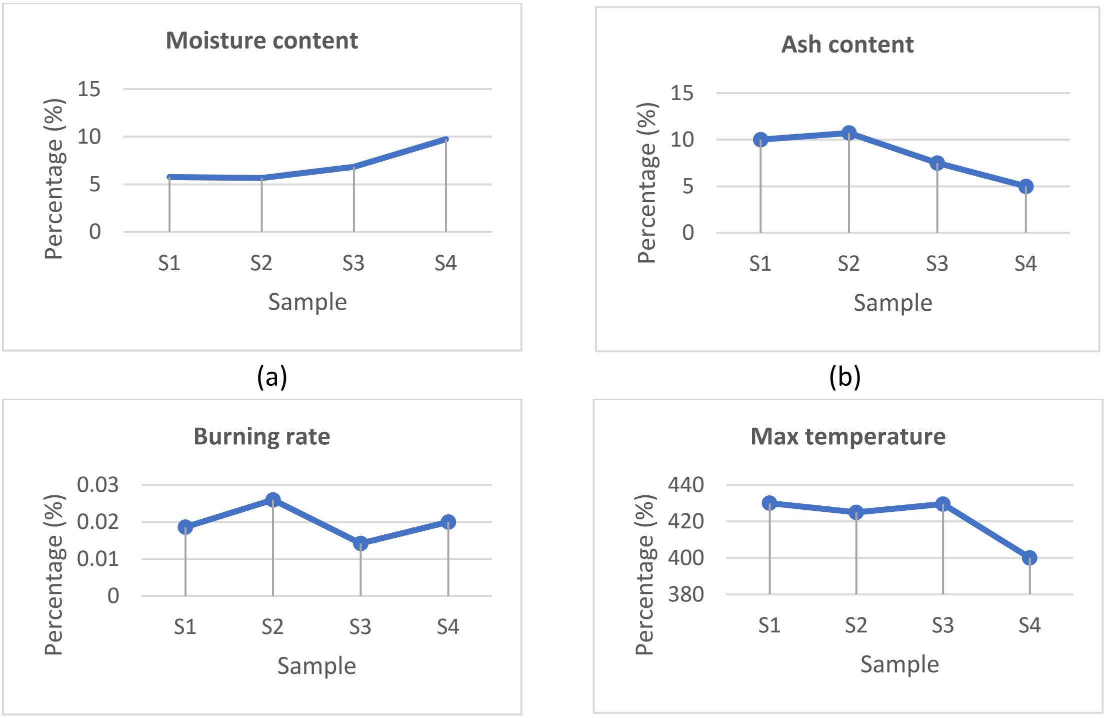


(a) (b)

(c) (d)

Figure 2. Performance test results: (a) Moisture content, (b) Ash content, (c) Burning rate, and (d) Maximum temperature

The presented result revealed that no single mixture outperformed all others across every parameter. Lower starch dosages favored higher peak temperatures and lower moisture contents, whereas higher starch contents reduced ash formation but were associated with elevated moisture and reduced thermal output, reflecting classical trade-offs reported in starch-bonded biomass briquettes (Demirbas, 2009; Kaliyan & Morey, 2010).s

4.7 Compliance with Indonesian National Standards

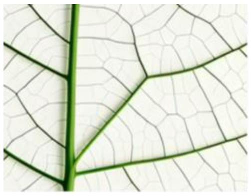
When benchmarked against SNI criteria, the 60 g starch formulation demonstrated the most balanced overall compliance, satisfying both moisture and ash-content requirements while maintaining moderate burning characteristics. The 20 g and 40 g starch briquettes met moisture limits but exceeded ash thresholds, whereas the 100 g formulation failed to comply with moisture requirements despite exhibiting the lowest ash content.

DISCUSSION

5.1 Influence of Binder Proportion on Briquette Performance

The experimental results confirm that starch dosage significantly influences the physical and combustion behavior of palm shell biochar briquettes; however, the effect is non-linear and involves clear trade-offs among performance indicators.

Lower starch additions (20 g) resulted in low moisture content and the highest combustion temperatures, suggesting a greater proportion of fixed carbon within the briquette matrix. in



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line with densification theory indicating that excessive binder dilutes combustible fractions and suppresses flame temperature (Antal & Gronli, 2003; Kaliyan & Morey, 2010). Nevertheless, these formulations also produced relatively high ash contents, indicating that reduced binder does not necessarily correspond to cleaner combustion residues.

Conversely, higher starch contents (100 g) minimized ash formation but retained excessive moisture and exhibited the lowest peak burning temperatures, outcomes consistent with prior observations that starch increases hygroscopicity and restricts internal air diffusion when used at elevated proportions (Demirbas, 2009; Tumuluru et al., 2011), which would reduce practical thermal efficiency in household applications. Intermediate starch proportions—particularly the 60 g formulation—achieved comparatively balanced behavior across parameters, combining acceptable moisture and ash levels with stable burning performance.

These results demonstrate that starch does not function solely as a mechanical binder but also modifies briquette pore structure, volatile release, and combustion dynamics, corroborating mechanisms proposed for starch-bonded biomass fuels (Kaliyan & Morey, 2010). Excess binder may occlude internal pore networks and retain water, whereas insufficient binder may permit greater mineral residue formation from the charcoal fraction, reinforcing the need for feedstock-specific binder optimization.

5.2 Contributions to Circular Bioenergy Systems

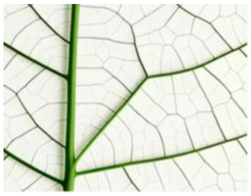
From a circular-economy perspective, the findings reinforce the feasibility of converting palm shell residues into standardized renewable fuels using low-technology processes, consistent with decentralized waste-to-energy pathways (Kirchherr et al., 2017; Scarlat et al., 2015). The identification of an intermediate starch dosage that satisfies regulatory thresholds highlights how formulation optimization can improve resource efficiency and reduce waste generation within agro-industrial systems, aligning with circular-bioeconomy frameworks emphasizing cascading use of biomass and local value retention (D'Amato et al., 2017).

Importantly, the results caution against simplistic assumptions that minimizing binder content automatically maximizes sustainability. Instead, circular bioenergy strategies must balance energy efficiency, regulatory compliance, and material durability to ensure that waste-derived fuels are technically viable and socially acceptable.

Embedding briquette production within palm-growing regions further exemplifies localized industrial symbiosis, whereby agricultural residues are transformed into energy carriers for nearby households or processing facilities, thereby shortening supply chains and reducing transport-related emissions (Boons et al., 2017; Chertow, 2007).

5.3 Managerial and Policy Implications

For practitioners, the findings suggest that moderate starch dosages—rather than extreme low or high levels—are most suitable for meeting fuel-quality standards, echoing recommendations from biomass-densification research that emphasizes calibration of binder levels to specific feedstocks and compaction regimes (Kaliyan & Morey, 2009; Tumuluru et al., 2011). Small-scale producers should therefore adopt formulation testing protocols prior to commercialization rather than relying on heuristic binder additions.



Policy makers and rural-energy programs may use these results to design technical guidelines for community briquetting initiatives and to promote certification schemes that ensure consistent product quality. Support for pilot-scale trials and training programs could further accelerate the diffusion of circular bioenergy technologies within palm-producing regions.

5.4 Comparison with Prior Studies

The present study extends previous biomass briquetting research by demonstrating that binder optimization for palm shell feedstocks involves multiple interacting performance criteria rather than a single dominant metric. While earlier work often emphasizes calorific value or ignition behavior, the combined evaluation of moisture, ash, burning rate, and temperature provides a more holistic basis for assessing fuel suitability (Kaliyan & Morey, 2010; Tumuluru et al., 2011). The observed performance of the 60 g formulation underscores the importance of feedstock-specific experimentation, as optimal binder windows differ across biomass types and carbonization conditions.

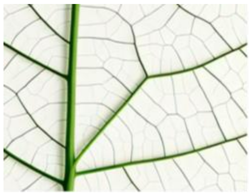
The findings also complement earlier investigations on decentralized shell carbonization systems in Aceh, which documented strong temperature–yield and temperature–ash relationships across reactor chambers (Amri et al., 2021a; Amri et al., 2021b). Together, these results suggest that downstream briquetting optimization must be integrated with upstream carbonization control if palm-shell residues are to be fully valorized within circular-energy systems.

5.5 Limitations and Directions for Future Research

The study is limited by its focus on a single binder material and by the absence of mechanical durability testing and emissions measurements. Future research should therefore incorporate compressive-strength assessments, particulate-emission analysis, and life-cycle assessment to quantify environmental trade-offs associated with binder optimization and decentralized briquette production (Cabeza et al., 2014; ISO 14040, 2006). Further investigation into carbonization temperature, particle-size distribution, and alternative bio-based binders would strengthen understanding of how briquette formulations can be optimized for circular-energy deployment.

CONCLUSION

This study evaluated palm shell biochar briquettes bonded with corn starch as renewable solid fuels for circular bioenergy systems, situating the experimental program within contemporary circular-economy and industrial-ecology frameworks that emphasize waste valorization and localized energy loops (Kirchherr et al., 2017; Chertow, 2007). Four binder formulations were experimentally assessed against Indonesian National Standards in terms of moisture content, ash content, burning rate, and peak burning temperature.



The results demonstrate that starch dosage exerts a complex influence on briquette performance, consistent with earlier densification and combustion studies showing that binders simultaneously affect pore structure, hygroscopicity, and effective fixed-carbon fractions (Kaliyan & Morey, 2010; Tumuluru et al., 2011). Lower binder levels favored high combustion temperatures and reduced moisture but were associated with elevated ash content, whereas high starch additions reduced ash formation yet caused excessive moisture retention and diminished thermal output, in line with observations reported for starch-bonded biomass fuels (Demirbas, 2009). Among the tested formulations, the 60 g starch mixture offered the most balanced overall performance and the strongest conformity with regulatory thresholds, highlighting the importance of identifying feedstock-specific binder optima rather than relying on extreme formulations.

These findings indicate that intermediate binder proportions may provide optimal trade-offs between energy efficiency and material stability in palm shell briquettes. From a circular-systems perspective, the study confirms the potential of agro-industrial residues to function as renewable energy carriers when formulation design is carefully optimized, reinforcing broader arguments that decentralized briquetting can contribute to circular bioeconomy transitions in palm-producing regions (D'Amato et al., 2017; Scarlat et al., 2015).

Nevertheless, the research is constrained by its laboratory scale and by the absence of durability testing and life-cycle analysis. Future work should expand binder types, incorporate mechanical-strength and emissions testing, and evaluate techno-economic performance at the pilot scale, consistent with calls for integrated environmental and systems assessment in sustainable-energy research (Cabeza et al., 2014; ISO 14040, 2006). Such efforts will be essential for translating experimental briquette formulations into scalable circular bioenergy solutions for palm-producing regions.

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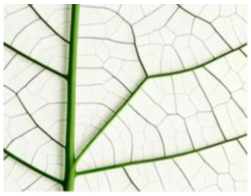

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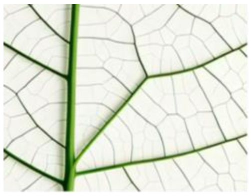

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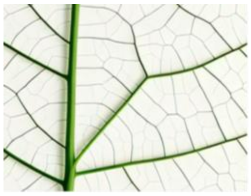

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