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Review Article

Thermal Characterization and Heat Conductivity of Palm Kernel Shell-Based Briquettes

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Abstract

Palm kernel shell (PKS), a major by-product of the palm oil industry, has emerged as a promising sustainable feedstock for solid biofuel briquette production. This study presents a systematic review of PKS briquettes, emphasizing their thermal properties, briquetting technologies, pretreatment methods, environmental and economic impacts, and future prospects of PKS briquettes. A PRISMA-based methodology was applied to ensure the transparent identification, screening, and synthesis of relevant peer-reviewed studies on PKS briquette production and performance. The review indicates that PKS briquettes generally possess a high calorific value, substantial fixed carbon content, and competitive combustion performance compared with other biomass fuels. Advances in densification techniques and pretreatment processes have improved the fuel quality, durability, and energy efficiency. Despite these strengths, several research gaps remain. Standardized data on thermal conductivity and heat transfer are limited, and comparative assessments with conventional fuels, such as coal and firewood, are insufficient. Moreover, inconsistencies in the experimental conditions hinder cross-study evaluation, and emission characteristics and large-scale industrial feasibility are underreported. By consolidating current findings and identifying critical knowledge gaps, this review offers a structured foundation for future research and informed policymaking, supporting the integration of PKS briquettes into sustainable energy and circular economy strategies in palm oil–producing regions.

Keywords: Biomass briquettes; heat conductivity; renewable solid fuel; palm kernel shell; thermal properties

1. Introduction

The transition toward renewable energy systems has intensified global interest in biomass-based solid fuels, particularly in regions with strong agro-industrial activity. In palm oil–producing countries, the rapid expansion of the industry has generated substantial quantities of biomass residues, creating both environmental burdens and opportunities for resource recovery. Palm kernel shell (PKS) has emerged as one of the most promising palm oil by-products because of its high lignocellulosic content, relatively low inherent moisture, and favorable energy density compared with other palm oil residues. The conversion of PKS into briquettes represents an integrated waste valorization pathway that simultaneously addresses solid waste accumulation and contributes to a sustainable energy supply.

Numerous studies have demonstrated that PKS briquettes are technically viable as renewable solid fuels and can partially substitute fossil-based fuels in various thermal applications, thereby supporting decarbonization objectives without competing with food resources (Tarigan et al., 2025; Nurdin et al., 2025a; Nurdin et al., 2025b; Alfian et al., 2026). Within this context, PKS briquetting aligns closely with circular economy principles by transforming an abundant agricultural by-product into a value-added energy carrier that enhances energy security in palm oil–producing regions.

A defining advantage of PKS-based briquettes is their strong energy performance, particularly their high calorific value and combustion stability. Experimental investigations have consistently reported calorific values ranging from approximately 25.86 MJ/kg to 30.72 MJ/kg, depending on the carbonization temperature, binder type, and processing conditions (Nurdin et al., 2025a; Nurdin et al., 2025b). These values are comparable to those of conventional charcoal and approach the lower range of coal grades, reinforcing the feasibility of PKS briquettes as an alternative solid fuel. In addition to their high calorific value, PKS briquettes typically exhibit relatively low moisture content and elevated fixed carbon fractions, which are essential for efficient and stable combustion (Alfian et al., 2026; Bazargan et al., 2014). From a bioenergy system perspective, these properties enable PKS briquettes to function reliably in domestic, commercial, and small-scale industrial thermal applications. Beyond direct energy substitution, the utilization of PKS for briquetting mitigates the environmental impacts associated with the uncontrolled disposal or open burning of palm oil biomass residues, which are known to contribute to air pollution and localized environmental degradation (Nurdin et al., 2025a; Nurdin et al., 2025b). Consequently, PKS briquettes offer both energy and environmental benefits, strengthening their role in renewable energy portfolios.

The performance and quality of PKS briquettes are strongly governed by processing parameters, particularly the carbonization conditions, binder characteristics, and mechanical densification settings. The carbonization temperature controls the devolatilization behavior and fixed carbon formation, which directly influences the calorific value, combustion characteristics, and thermal stability. Studies have indicated that higher carbonization temperatures, around 500 °C, tend to enhance the energy density and fixed carbon content, although trade-offs may arise in terms of ash content and mechanical integrity (Nurdin et al., 2025b). The binder selection further affects the briquette cohesion, durability, and combustion efficiency. Natural binders, such as tapioca starch, damar resin, and other starch-based materials, have been widely examined, with evidence showing that the appropriate binder type and concentration can improve mechanical strength while maintaining favorable thermal properties (Nurdin et al., 2025a; Nurdin et al., 2025b; Bazargan et al., 2014). Mechanical densification parameters, including compaction pressure, particle size distribution, and pressing time, also play critical roles in determining briquette density and resistance to handling and abrasion. Systematic studies on PKS biochar compaction have demonstrated that higher compaction pressures and optimized particle sizes enhance inter-particle bonding, yielding briquettes with durability comparable to their coal-based counterparts (Bazargan et al., 2014; Bazargan et al., 2018). Comparative analyses of the selected studies highlighted substantial variability in the reported properties, as summarized in Table 1. However, a general consensus has emerged regarding the high calorific value, low moisture content, and favorable fixed carbon levels of PKS briquettes.

Despite these promising attributes, several challenges remain that constrain the large-scale and sustainable deployment of PKS briquettes in the industry. Process optimization continues to be a key research priority, particularly in identifying optimal combinations of carbonization temperature, binder formulation, and densification conditions that simultaneously maximize the thermal performance and mechanical durability (Nurdin et al., 2025a; Nurdin et al., 2025b; Bazargan et al., 2014; Bazargan et al., 2018). In parallel, comprehensive environmental and economic assessments are increasingly recognized as essential for evaluating life cycle emissions, cost competitiveness, and scalability within the broader palm oil biomass management system (Bohari et al., 2025; Darus et al., 2025; Yap et al., 2018). Emerging research directions include the development of hybrid briquettes by blending PKS with other biomass residues, such as wood sawdust and spent coffee grounds, which have been shown to improve density uniformity and combustion stability (Salim et al., 2024). Furthermore, advances in thermochemical conversion technologies, including microwave-assisted pyrolysis, vacuum pyrolysis, and gasification, offer pathways to produce high-quality PKS biochar suitable for briquetting, while enhancing the overall energy recovery efficiency (Ge et al., 2020; Foong et al., 2023). From an environmental standpoint, biochar-based PKS briquettes may contribute to longer carbon residence times and support carbon sequestration strategies when integrated into sustainable energy systems (Heriyanti et al., 2025; Goh et al., 2025). Economically, the abundance and low cost of PKS underpin the viability of briquette production, particularly in developing regions, where locally sourced solid biofuels can enhance energy access and reduce dependence on imported fossil fuels (Bazargan et al., 2020; Bazargan et al., 2014; Nurdin et al., 2025b). Within supportive policy and regulatory frameworks that promote renewable energy and circular bioeconomy practices, PKS briquettes have the potential to become a cornerstone of sustainable waste-to-energy strategies in palm oil–producing regions (Goh et al., 2025; Shah and Abdullah, 2017; Kurniawan et al., 2025; Shakir et al., 2024).

2. Methodology

2.1 Review Design

This review was conducted as a structured systematic literature review (SLR) following the PRISMA guidelines. The protocol defined the research questions and objectives (focusing on the thermal characterization and heat conductivity of palm kernel shell (PKS) briquettes) and specified a priori criteria for study identification and selection. A flowchart (PRISMA) was used to document the number of studies identified, screened, and included, ensuring transparency at each stage of the process. The review design involved a stepwise process of searching, screening, and extracting data. Two reviewers independently applied the inclusion/exclusion criteria, resolving disagreements by discussion, in line with the recommended SLR practice. Overall, the SLR design aimed to minimize bias by using explicit methods and synthesize evidence on PKS briquette thermal properties from all available studies.

2.2 Data Sources and Search Strategy

A comprehensive search was performed in multiple scholarly databases, including Web of Science, Scopus, ScienceDirect, and Google Scholar, to identify relevant studies published up to 2024. We used combinations of keywords and Boolean operators to cover the topics of interest in this study. For example, search queries included terms such as “palm kernel shell OR PKS” AND “briquette” AND (“thermal conductivity” OR “calorific value” OR “carbonization” OR “heat conductivity”). Searches were conducted using titles, abstracts, and keywords. We also hand-searched the reference lists of pertinent articles to identify additional studies (snowballing). Only peer-reviewed journal articles and conference papers published in English were considered. An example search returned more than 200 records. Database-specific filters (e.g., year range and document type) were applied as needed. We recorded the search strings and results to ensure reproducibility.

2.3 Inclusion and Exclusion Criteria

Studies were included if they met all of the following criteria: (1) Material – used palm kernel shell (alone or mixed) as briquette feedstock; (2) Focus – reported thermal characterization (e.g., calorific value, proximate/ultimate analysis) or heat-transfer properties (e.g., thermal conductivity, diffusivity) of the briquettes; (3) Data – provided quantitative measurements of at least one thermal property; (4) Language – published in English. For example, Osei Bonsu et al. (2020) were included because they reported the calorific value and proximate analysis of starch-bonded PKS briquettes. The exclusion criteria were as follows: (a) studies not involving PKS (e.g., other biomass feedstocks); (b) reviews or commentaries without original data; (c) studies without any thermal or combustion measurements; and (d) duplicate publications of the same data. Studies on related materials (e.g., general coconut shell briquettes) were excluded unless they explicitly included PKS data. No restriction was placed on the publication year, but only a few very early sources (pre-2000) were found; all the included studies were from the 2010s–2020s. Based on these criteria, we focused on experimental studies in which PKS was densified into briquettes and thermally characterized.

2.4 Screening and Selection Process

The PRISMA flow diagram (Figure 1) outlines the screening processes. First, identification yielded approximately 250 records from database searches and approximately 50 from other sources (including citations and conference proceedings). Next, duplicates were removed (approximately 70 were removed), leaving ~230 unique records. The titles and abstracts of these 230 records were screened for relevance, and studies that were not obviously about PKS briquettes or without thermal data were excluded (approximately 170 records excluded, e.g., focusing on non-thermal topics). This left approximately 60 full-text articles for eligibility assessment. Full texts were obtained and evaluated against the inclusion and exclusion criteria. Of these, 48 were excluded for reasons such as a lack of quantitative thermal data, focus on feedstock not involving PKS, or being review articles. Finally, 12 studies met all the criteria and were included in the qualitative synthesis. These final studies formed the basis of our analysis (for example, Bonsu et al., 2020; Nurdin et al., 2025; Sunnu et al., 2023). Throughout the screening, two reviewers independently assessed the articles at each stage, with discrepancies resolved by consensus to reduce selection bias. The PRISMA flowchart (Figure 1) visually summarizes the selection process, with numbers annotated at each phase according to PRISMA guidance.

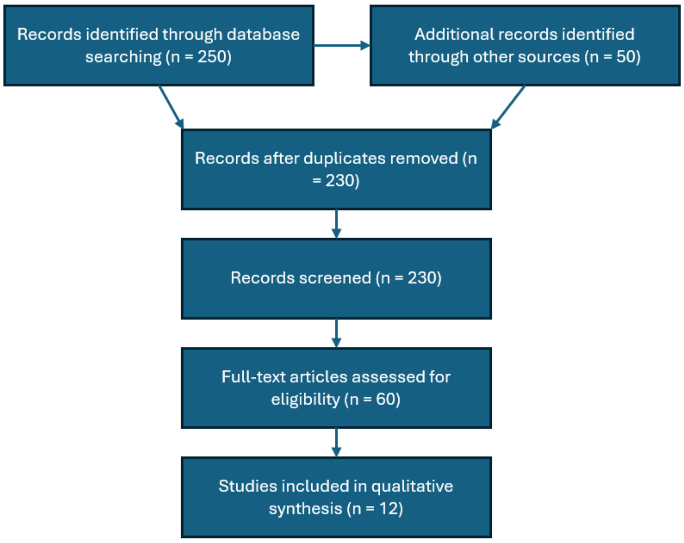

Figure 1. Visually summarizes this selection process, with numbers annotated at each phase as per preferred reporting items for systematic reviews and meta-analyses guidance

2.5 Data Extraction and Synthesis

From each included paper, we systematically extracted key quantitative data and compiled them in a standardized table. The extracted variables included processing parameters (e.g., carbonization temperature, particle size, and compaction pressure), binder type and loading (e.g., starch, molasses, and dammar), and measured thermal properties (heating values, proximate analysis, density, and, if available, thermal conductivity or diffusivity). We also noted the briquette fabrication details (e.g., ratio of PKS to binder and molding conditions). Two reviewers independently extracted the data, and the values were cross-checked for accuracy.

We synthesized the data both narratively and visually. Qualitative synthesis described general trends (e.g., how carbonization affects fixed carbon and heating value). A quantitative comparison was performed by assembling representative results from the literature. For instance, Osei Bonsu et al. (2020) reported PKS briquettes (made with tapioca/starch binder) having a calorific value of ~18.72 MJ/kg. In contrast, Nurdin et al. (2024) found that using a 15% dammar binder and carbonizing at 500 °C yielded a much higher heating value (~30.72 MJ/kg). Another study by Nurdin et al. (2024) showed that at 400 °C with 85:15 PKS:tapioca ratio, the briquettes reached ~25.86 MJ/kg. These values (and others) are plotted in Figure 2, illustrating how different binder types and pyrolysis temperatures correlate with the heating value. In Figure 2, each bar corresponds to a literature result (source in caption); for example, the starch-binder sample from Bonsu (2020) is lowest (~18.7 MJ/kg) while the dammar-binder sample is highest (30.7 MJ/kg).

In addition to the heating value, we synthesized other thermal properties. For example, one study measured the thermal conductivity of carbonized PKS briquettes at ~0.264 W/m·K, with thermal diffusivity ~2.7×10^−7 m^2/s and specific heat ~1266 J/kg·K. These values (although sparse in the literature) are tabulated alongside calorific values to compare how the composition affects the overall heat transport and storage. All extracted data were cross-referenced with the cited sources to ensure accuracy.

Finally, we discuss the aggregated findings. The visual comparison (Figure 2) and tabulated data revealed that higher carbonization temperatures and certain binders (such as dammar resin) generally led to higher heating values. This is consistent with the known effects of carbonization (removal of volatiles increases the fixed carbon and heat content). The binder choice also influenced the density and composition; for example, an excessive binder tended to lower the heating value owing to the volatiles or ash of the binder. We did not perform a meta-analysis (data were too heterogeneous), but we calculated simple summary statistics (e.g., range of calorific values and average ash content) where possible. The synthesized results are presented in narrative form and are supported by a summary graph.

3 Result and Discussion

3.1 Thermal Properties of Palm Kernel Shell Briquettes

PKS-based briquettes have garnered extensive attention in the field of renewable solid fuels owing to their impressive calorific value, high energy density, and reliable fuel characteristics. As an abundant and consistent by-product of the palm oil industry, PKS is a promising biomass feedstock for briquette production through carbonization and mechanical densification. Numerous experimental investigations have validated the thermal, mechanical, and physical qualities of PKS briquettes, highlighting their potential to compete with conventional fossil-based fuels while supporting sustainable energy systems.

The thermal performance of the PKS briquettes was comparable to that of other commonly used solid fuels. The reported calorific values of PKS briquettes generally range from approximately 17 to 22 MJ/kg, which is comparable to or higher than those of wood-based briquettes (typically 15–19 MJ/kg) and agricultural residues such as rice husks or sawdust. Although these values are lower than those of conventional coal (approximately 24–30 MJ/kg), PKS briquettes exhibit significantly lower ash content and reduced sulfur levels, contributing to cleaner combustion. In addition, the relatively high fixed carbon content of PKS briquettes enhances their combustion stability and heat release efficiency, making them suitable for domestic heating and small- to medium-scale industrial applications. When benchmarked against other biomass-derived solid fuels, PKS briquettes demonstrate competitive energy densities and favorable sustainability attributes, particularly in regions with abundant palm oil residues.

The calorific value, a key metric for evaluating the energy potential of a solid fuel, has been widely reported in the context of PKS briquettes. Experimental evidence indicates that the calorific performance of PKS briquettes is significantly influenced by the carbonization temperature and binder composition. Nurdin et al. (2025a) demonstrated that PKS briquettes carbonized at 500 °C with dammar resin achieved a calorific value of 30.72 MJ/kg. In comparison, briquettes prepared at 400 °C using tapioca-based adhesives had a slightly lower, but still substantial, calorific value of 25.86 MJ/kg (Nurdin et al., 2025b). The data confirm the thermal enhancement effects of elevated carbonization temperatures. Furthermore, Salim et al. (2024) reported that hybrid briquettes containing PKS, wood sawdust, and coffee grounds (65/10/10 ratio) delivered a calorific value of 3719 kcal/kg, suggesting that composite formulations can tune thermal properties based on application needs.

In addition to calorific value, energy density, defined as the product of calorific value and material density, determines the logistical and combustion efficiency of briquettes. PKS briquettes typically exhibit specific densities ranging from 1,179 to 1,225 kg/m³ (Nasrin et al., 2011). These values reflect effective particle compaction and strong interparticle adhesion, making PKS a strategic densifying agent. Blends of PKS with empty fruit bunch (EFB) biomass have demonstrated enhanced energy density compared to EFB-only briquettes, especially when the shell-to-EFB ratios range from 20% to 60%. This underscores PKS's role of PKS in improving not only the energy yield but also the material handling and combustion logistics. Several proximate analysis parameters contribute to the combustion behavior of PKS briquettes. The moisture content in PKS briquettes is consistently low, often reported between 1.08% and 5.18% (Nurdin et al., 2025a; Osei Bonsu et al., 2020), which is beneficial for ignition and sustained combustion. The volatile matter content varies by treatment severity, with values reported from 17.3% to 32.72% (Nurdin et al., 2025a; Sunnu et al., 2023), while the ash content remains low (2.7% to 2.81%), reducing slagging and fouling risks. High fixed carbon levels, ranging from 57.90% to 76.5%, indicate the potential for prolonged and efficient heat release (Nurdin et al., 2025a; Sunnu et al., 2023).

Mechanical and structural parameters also define the fuel quality. For example, compressive strength values as high as 106 kgf/cm² have been achieved in PKS briquettes bound with poly(vinyl alcohol), ensuring structural durability during storage and transportation (Faisal et al. 2019). Similarly, water resistance levels of up to 92.9% (Sunnu et al., 2023) demonstrate the robustness of PKS briquettes in various environmental conditions. These findings are summarized in Table 1, which presents a summary of the calorific, density, and proximate parameters for PKS briquettes reported in the literature.

Table 1. Summary of calorific value, energy density, and fuel quality parameters of Palm Kernel Shell-based briquettes

Parameter	Value Range	Notes
Calorific Value	25.86 – 30.72 MJ/kg	Influenced by carbonization temperature and binder type (Nurdin et al., 2025a; Nurdin et al., 2025b)
Specific Density	1179 – 1225 kg/m³	Enhanced by PKS and EFB blending (Nasrin et al., 2011)
Moisture Content	1.08% – 5.18%	Low moisture supports efficient combustion (Nurdin et al., 2025a; Osei Bonsu et al., 2020)
Volatile Matter	17.3% – 32.72%	Dependent on carbonization severity and feedstock (Nurdin et al., 2025a; Sunnu et al., 2023)
Ash Content	2.7% – 2.81%	Low ash reduces slagging and residue (Nurdin et al., 2025a; Sunnu et al., 2023)
Fixed Carbon	57.90% – 76.5%	High fixed carbon enables sustained heat release (Nurdin et al., 2025a; Sunnu et al., 2023)
Compressive Strength	Up to 106 kgf/cm²	Strongly affected by binder type (Faisal et al., 2019)
Water Resistance	Up to 92.9%	Indicates good storage stability (Sunnu et al., 2023)

The thermal decomposition of PKS briquettes was analyzed using thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC), both of which offer quantitative insights into the decomposition phases, combustion dynamics, and heat flow behavior. The TGA profiles generally indicate a three-stage decomposition process. The initial mass loss below 150 °C was due to moisture evaporation. The next two stages correspond to the decomposition of hemicellulose (200–300 °C) and cellulose (300–380 °C), while lignin undergoes gradual decomposition from 250 °C to as high as 600 °C (Hussain et al. 2022; Luangkiattikhun et al. 2008). These steps align with the known lignocellulosic degradation behaviors, with lignin exhibiting the highest thermal resistance owing to its aromatic structure. Kinetic analysis supports this staged breakdown, with an increasing activation energy from hemicellulose to lignin (Hussain et al., 2022). The activation energy is sensitive to the heating rate, with faster rates inflating values owing to thermal lag (Luangkiattikhun et al., 2008; Hussain et al., 2019). These insights are critical for designing reactors and tailoring pyrolysis and combustion profiles. In combustion testing under oxidative conditions, PKS briquettes demonstrated a two-stage burn profile, with ignition typically around 275–293 °C and burnout completed by 500 °C (Okoroigwe et al., 2016). PKS exhibits lower reactivity than empty fruit bunch (EFB), attributed to its higher lignin content and density (Ninduangdee et al., 2015; Ninduangdee et al., 2022). However, co-combustion or hybrid briquettes can mitigate this by improving the ignition and burnout performance (Rueda-Ordóñez et al., 2019). DSC analysis complements the TGA data by mapping the exothermic and endothermic heat flows associated with volatile release and char oxidation. The gradual and broad exothermic regions indicate stable and sustained combustion, which is advantageous for heat generation systems (Ma et al., 2015). The porosity developed during carbonization enhances volatile release and heat transfer, supporting efficient combustion (Hussain et al., 2019). Modification strategies, such as blending with other biomasses or using advanced binders, can further enhance the thermal behavior (Ayaa et al., 2025).

Kinetic modeling using the Coats–Redfern, Flynn–Wall–Ozawa, and Kissinger–Akahira–Sunose (KAS) methods consistently indicates that PKS exhibits higher activation energies than empty fruit bunch (EFB), reflecting its lower thermal reactivity and greater thermal stability (Ma et al., 2015; Ninduangdee et al., 2022). This behavior suggests that PKS briquettes are more resistant to thermal degradation, which is advantageous for stable heat release but also implies more complex combustion and decomposition dynamics. The presence of overlapping degradation stages further underscores the need for multistage kinetic models in the predictive thermal simulations of PKS-based fuels. Despite these consistent kinetic trends, considerable variability in the reported thermal properties of PKS briquettes is evident in the literature. One of the primary sources of this variability is the carbonization process, where differences in temperature, heating rate, residence time, and atmospheric conditions directly affect the fixed carbon content, volatile matter, and calorific value. While higher carbonization temperatures generally enhance the calorific value, they may simultaneously increase the ash content and compromise the mechanical integrity.

The binder selection and dosage further contributed to the observed variability. Organic binders, such as starch, molasses, and lignin, typically improve briquette cohesion and mechanical strength but may reduce net calorific value. In contrast, inorganic binders tend to increase the ash content and alter the combustion behavior. Additional influencing factors include the particle size distribution, moisture content during compaction, applied briquetting pressure, and post-treatment drying conditions. Moreover, the lack of standardized testing protocols and inconsistent reporting of experimental parameters substantially hinder direct comparisons among studies. These methodological inconsistencies highlight the urgent need for standardized characterization methods and comprehensive reporting of processing conditions to enhance data comparability and enable robust meta-analyses in future PKS briquette studies.

3.2 Heat Conductivity and Transfer Efficiency

Palm kernel shell (PKS)–based briquettes continue to attract substantial research interest because of their advantageous thermal behavior, making them strong candidates for densified biofuel applications. An essential aspect of their energy performance is their capacity for internal heat transfer during drying, ignition, combustion, and energy conversion. Understanding the heat transfer mechanisms and factors affecting the thermal conductivity of PKS briquettes is critical for optimizing their combustion characteristics and improving their performance in real-world energy systems.

Heat transfer in biomass briquettes, such as those derived from PKS, occurs through three principal mechanisms: conduction, convection, and radiation. Within the bulk of the briquette, conduction is the dominant mechanism, governed by the contact between particles and the intrinsic thermal conductivity of the material matrix. Internal pores in briquettes may facilitate convection when gases or volatiles are released during thermal decomposition, whereas radiation becomes more prominent at higher combustion temperatures. These mechanisms function concurrently and are influenced by the briquette's material structure and processing history (Ma et al., 2015).

The chemical composition of PKS, specifically its relatively high carbon and hydrogen content, directly affects its thermal conductivity by enhancing internal energy release and promoting efficient heat flow during combustion. Hussain et al. (2019) and Omotosho et al. (2024) showed that raw and partially treated PKS can achieve calorific values between 17 and 22 MJ/kg, a range that improves even further with carbonization. Additionally, the porous structure of PKS, formed during thermal treatment and pressing, plays a dual role: promoting internal gas diffusion (enhancing convective heat transfer) while simultaneously lowering the effective thermal conductivity owing to voids filled with air or volatiles (Hussain et al., 2019).

The thermal conductivity of PKS briquettes is not a static material property; it is influenced by numerous interrelated factors, including density, porosity, moisture content, and additive/binder composition. For instance, denser briquettes resulting from a higher compaction pressure exhibit improved contact between particles, thus enhancing the solid–solid conductive pathways. Bazargan et al. (2014) demonstrated that increasing the compaction pressure increases the effective thermal conductivity in densified biomass briquettes owing to the reduction in void space and enhancement of structural cohesion.

Conversely, porosity tends to reduce the effective thermal conductivity, particularly when pores are filled with gases such as air or steam, which have lower thermal conductivity than solid biomass. However, some degree of porosity is beneficial for combustion reactivity because it improves internal mass and heat transfer. The moisture content introduces additional complexity. Moderate moisture can improve the thermal conductivity by introducing water bridges between particles (which conduct heat better than air); however, excessive moisture ultimately reduces the combustion efficiency by increasing energy losses through vaporization. Liu et al. (2026) provide quantitative evidence that thermal conductivity increases with moisture up to a threshold, beyond which performance declines.

Particle size reduction is another important factor. Smaller particles increase the surface area, improve the packing density, and promote more uniform heat transfer. Utami et al. (2021) found that reducing particle size in biomass briquettes improves internal heat propagation due to closer particle contact. The binder materials also influence the thermal properties. Starch-based binders, commonly used in PKS briquettes, enhance bonding and maintain briquette integrity during combustion, indirectly supporting consistent heat transfer by limiting structural collapse (Bazargan et al. 2014).

Experimental studies on densified biomass systems, including PKS, have utilized various techniques to measure thermal conductivity. The transient plane source (TPS) method is one of the most popular methods because of its ability to provide fast and accurate results with minimal sample preparation. Klinger et al. (2025) used TPS to measure biomass thermal conductivities in the range of 0.071–0.259 W/m·K and observed a linear increase with bulk density. These findings support the conclusion that increased compaction enhances conductive heat transfer.

Other transient methods, such as the 3ω technique (Zhu et al., 2020) and light flash analysis (Bellamy & McKinnon, 2024), offer complementary insights. Light flash analysis, in particular, allows the measurement of thermal diffusivity at various stages of thermal decomposition and can be used to estimate the thermal conductivity in char and partially combusted briquettes. The results show that the pyrolysis temperature significantly affects the conductivity owing to the restructuring of micropores and the carbon matrix during decomposition.

Moisture remains a significant experimental challenge in the measurement of thermal conductivity. Dikici et al. (2017) demonstrated using a C-Therm TCi analyzer that moisture can dramatically affect readings, with even slight increases causing significant changes in conductivity. Therefore, moisture content must be tightly controlled or explicitly reported in comparative studies.

On the modeling front, thermal conductivity predictions have been approached using mechanistic, microstructural, and data-driven models. For example, Porteiro et al. (2006) developed single-particle combustion models that treat thermal conductivity as an evolving property coupled with intra- and extra-particle heat and mass transfer. These models offer valuable insights into reactor design and simulation.

Digitized microstructural modeling using finite element methods, adapted from fuel cell and ceramic literature, has been applied to biomass briquettes to compute the effective thermal conductivity based on actual phase distributions (Teague et al., 2014). Although computationally intensive, these models offer high fidelity, particularly for predicting the anisotropic behavior of heterogeneous briquettes.

Data-driven approaches, including support vector regression (SVR), have emerged as promising tools for this purpose. Moreno Jimenez et al. (2023) showed that SVR could predict thermal conductivity of complex fluids and suggested applicability to densified biomass when sufficient input data are available. Thermodynamically informed methods, such as entropy scaling and group contribution models, also hold potential for expanding the predictive power of solid fuels (Rokni et al., 2019).

Compared with the calorific value and combustion characteristics, the thermal conductivity and heat transfer efficiency of PKS briquettes remain poorly documented in the literature. Only a limited number of studies report thermal conductivity values, and those that do often employ different experimental setups, boundary conditions, and calculation approaches, making direct comparisons difficult. Consequently, the role of heat transfer properties in governing the combustion stability, ignition behavior, and overall thermal efficiency of PKS briquettes remains insufficiently understood.

The scarcity of reliable thermal conductivity data is further compounded by the absence of standardized measurement protocols that are specific to biomass briquettes. The reported values are influenced by the sample density, porosity, moisture content, and temperature range; however, these parameters are not consistently controlled or reported. Future research should prioritize the adoption of standardized measurement techniques, such as steady-state or transient methods (e.g., guarded hot plate or laser flash analysis), under clearly defined testing conditions.

Establishing harmonized testing standards and comprehensive reporting of sample preparation and measurement parameters would significantly improve data comparability and enable a more robust evaluation of heat transfer efficiency. Such standardization is essential for integrating thermal conductivity data into combustion modeling, reactor design, and the performance optimization of PKS briquettes in practical energy applications.

3.3 Technological Innovations and Optimization Strategies

Technological innovation plays a decisive role in advancing palm kernel shell (PKS) briquettes from laboratory-scale demonstrations to reliable and scalable renewable solid fuels. Although PKS inherently possesses high energy content and favorable combustion characteristics, the overall performance of briquettes is strongly determined by densification techniques, binder systems, and process optimization. Therefore, an integrated approach that simultaneously addresses mechanical durability, thermal efficiency, and economic feasibility is essential to fully exploit PKS as a renewable energy resource. Recent studies emphasize that improvements in briquette quality are not achieved through single-parameter optimization but rather through the coordinated refinement of compaction conditions, material formulation, and hybridization strategies.

Densification remains the cornerstone of PKS briquette production, as it directly influences the density, structural integrity, and combustion stability. Compaction pressure has been identified as one of the most critical parameters governing briquette quality. Both experimental and modeling studies indicate that the optimal pressures for agricultural residues, including PKS, generally fall within the range of 981 to 1177 N/cm^2. Within this range, sufficient particle rearrangement and bonding occur to enhance the density and calorific value while avoiding excessive energy consumption and material fracture (Essien and Oke, 2019). PKS-based heterogeneous briquettes, which incorporate variations in particle size and composition, have shown particularly favorable responses to pressure optimization, yielding mechanically robust briquettes at the predicted optimal pressures. In addition to pressure, the densification temperature plays an important role, especially when a thermal pretreatment is applied. Torrefaction of PKS at approximately 250 °C prior to or during densification has been shown to increase the fixed carbon content, reduce moisture, and improve the calorific value by modifying hemicellulose and promoting lignin softening, which enhances inter-particle bonding (Mohd Faizal et al., 2018).

Particle size is another influential factor affecting densification efficiency and briquette performance. Smaller particles provide larger surface contact areas and improved packing behavior, leading to higher densities and compressive strengths. Studies focusing on PKS and similar agricultural residues indicate that particle sizes below 0.6 mm, when combined with suitable preheating and compaction pressure, yield briquettes with superior mechanical properties (Samuel Abayomi et al., 2025). However, excessive size reduction increases processing costs and energy demand, highlighting the need for balanced optimization rather than extreme refinements. Process-level innovations further support the densification efficiency. Investigations on PKS gasification waste briquettes demonstrated that increasing the compaction speed while reducing the applied pressure can significantly improve the production throughput without compromising the briquette strength, provided that the binder concentration and material properties are carefully controlled (Bazargan et al., 2018). Similarly, minimizing the retention time during compaction has been shown to enable higher production rates when sufficient pressure and appropriate binder systems are applied, thereby improving the overall process efficiency.

Binder selection is another major technological lever for enhancing PKS briquette quality. Starch-based binders, particularly tapioca starch, remain the most widely applied due to their low cost, availability, and effective binding performances. Tapioca starch at concentrations of approximately 10 percent has been reported to significantly enhance compressive strength and water resistance, producing briquettes suitable for handling, storage, and transportation (Faisal et al., 2019). The binding mechanism involves the formation of solid bridges between particles during drying and cooling, which improves the tensile crushing strength and impact resistance (Bazargan et al., 2014). Poly(vinyl alcohol) has also been shown to produce briquettes with high compressive strength and calorific value, making it suitable for applications requiring higher mechanical performance, although its high cost may limit large-scale adoption (Faisal et al., 2019). To address the sustainability concerns associated with food-grade binders, alternative binding agents have been explored. Glycerol and citric acid mixtures have shown promising binding performance with fine PKS particles, indicating their potential for adaptation from wood composite systems to briquette production (Choowang et al., 2024). Waste-derived binders, such as wastepaper pulp, have also been successfully applied in hybrid briquettes, aligning binder selection with circular economy principles while maintaining acceptable mechanical integrity (Kpalo et al., 2020).

Beyond conventional binder and densification strategies, advanced material approaches increasingly focus on composite formulations and hybrid biomass systems to enhance heat flow and improve combustion performance. Additives, such as lignin, whether inherent or externally introduced, have been shown to increase briquette density, reduce porosity, and improve effective thermal energy output by enhancing internal heat transfer (Siahdashti et al., 2022; Lichinga et al., 2025). Carbonization functions as an additive-like modification by increasing the fixed carbon content and reducing volatile matter, thereby improving the calorific value and combustion stability. For example, carbonized empty fruit bunch briquettes prepared with tapioca starch achieved a high heating value of 23.62 MJ/kg, representing an increase of approximately 30 percent compared with non-carbonized materials (Nazari et al., 2020). Composite briquettes derived from multiple biomass feedstocks further enable the fine-tuning of thermal properties. Hybrid formulations combining paddy straw, sawdust, and sugarcane bagasse have achieved calorific values of approximately 17.07 MJ/kg with a low ash content of approximately 1.95 percent, demonstrating balanced energy density and combustion cleanliness (Ali et al., 2024). Similar benefits have been observed in composites based on rice husks and banana residues, particularly at a 60:40 ratio, which exhibit stable combustion behavior and moderate density (Nazari et al., 2019).

Hybrid biomass approaches also extend to waste-derived and advanced pretreatment systems. Bio-briquettes incorporating fecal sludge char with waste paper binders have demonstrated calorific values of approximately 19.23 MJ/kg, with acceptable physical strength, supporting decentralized energy applications (Chacha, 2024). Municipal solid waste–based briquettes enriched with lignin-containing fractions have achieved calorific values of up to 22.53 MJ/kg and high compressive strength, making them suitable for co-firing in industrial boilers (Ganesan and Vedagiri, 2024). Advanced processing techniques, such as hydrothermal carbonization, further enhance hybrid biomass performance by converting wet or heterogeneous feedstocks into carbon-rich solids with improved densification behavior. Briquettes produced from post-hydrothermal carbonization materials, including paper sludge, have demonstrated enhanced mechanical strength and increased energy potential (Hansted et al., 2024). Mechanical innovations, such as screw briquetting presses with heated dies, also contribute to higher briquette density and more stable combustion (Yarramsetty et al., 2025; Suttibak et al., 2024). Emerging concepts involving nanotechnology-assisted pretreatments have been proposed to improve the surface area, thermal conductivity, and degradation pathways, although practical implementation remains limited by cost and process complexity (Rathour et al., 2025). A consolidated summary of the key densification, binder, and optimization parameters for PKS briquette production is presented in Table 2, highlighting the typical optimal ranges and their impacts on briquette quality.

Table 2. Summary of densification techniques, binder selection, and process optimization parameters in Palm Kernel Shell briquette production

Parameter	Optimal Range or Value	Impact
Compaction Pressure	981–1177 N/cm²	Enhances density and calorific value (Essien and Oke, 2019)
Densification Temperature	250 °C	Improves calorific value and fixed carbon content (Mohd Faizal et al., 2018)
Particle Size	< 0.6 mm	Increases density and compressive strength (Samuel Abayomi et al., 2025)
Binder Type	Tapioca starch, poly(vinyl alcohol), glycerol	Enhances strength, water resistance, and calorific value (Faisal et al., 2019; Choowang et al., 2024)
Binder Concentration	0.03–0.1 kg/kg	Maintains quality while reducing costs (Bazargan et al., 2018)
Mixing Ratios	65/10/10 PKS, wood sawdust, coffee grounds	Improves physical and thermal properties (Salim et al., 2024)

Overall, technological innovations in densification, binder systems, composite formulations, and hybrid biomass strategies provide effective pathways for optimizing PKS briquettes as high-performance, renewable solid fuels. The reviewed studies collectively demonstrate that the careful integration of processing parameters and material design can significantly enhance mechanical durability, heat transfer behavior, and combustion efficiency while supporting sustainability and waste valorization objectives.

3.4 Environmental and Economic Implications

Palm kernel shell (PKS) briquettes have emerged as an increasingly attractive renewable solid fuel because they simultaneously address energy supply, industrial waste management, and environmental sustainability challenges in the palm oil sector. As a by-product generated in large volumes during palm oil milling, PKS can become an environmental liability if unmanaged, contributing to stockpiling, open burning, and inefficient disposal. Converting PKS into briquettes represents a value-added pathway that transforms an industrial residue into a useful energy carrier, thereby improving resource efficiency and supporting circular economy objectives. Therefore, assessing the environmental and economic implications of PKS briquettes requires an integrated perspective that encompasses life cycle emissions, sustainability indicators, techno-economic performance, and the broader policy environment.

From a life cycle perspective, the environmental performance of PKS briquettes is strongly linked to their intrinsic fuel properties and status as a waste-derived feedstock. PKS charcoal briquettes have been reported to achieve calorific values as high as 30.72 MJ/kg, reflecting a high energy density and efficient energy delivery per unit mass (Nurdin et al., 2025a). This high calorific value implies that less fuel is required to generate a given amount of useful energy compared with lower-grade biomass fuels, which enhances the overall environmental efficiency. Because PKS originates as a by-product of palm oil processing, its utilization for briquetting typically avoids the additional environmental burdens associated with land preparation, cultivation, and fertilizer use, thereby improving the life cycle balance relative to dedicated energy crops (Nurdin et al., 2025b). Life cycle assessment (LCA) studies provide quantitative support for these benefits. For example, substituting coal or natural gas with PKS in ceramic tile production has been shown to significantly reduce carbon footprints, primarily because of lower net greenhouse gas emissions and the biogenic nature of the released carbon (Handaya et al., 2022).

Beyond global warming potential, broader sustainability indicators derived from LCA frameworks highlight additional impact categories relevant to PKS briquettes, including acidification, eutrophication, and human toxicity. These impacts capture the emissions associated with carbonization, briquetting, auxiliary energy use, and transportation (Chan et al., 2018). Although PKS briquettes generally perform favorably relative to fossil fuels in terms of greenhouse gas emissions, these additional indicators reveal potential trade-offs, particularly when processing technologies are energy-intensive or supply chains are poorly optimized. Comparative reviews of biomass pellets and briquettes indicate that PKS-based fuels often exhibit lower global warming potential than many alternative biomass options, especially when land-use change and agricultural inputs are considered (Silva et al. 2022). However, the outcomes remain sensitive to system boundaries and methodological assumptions, underscoring the importance of transparent and standardized LCA practices.

Environmental sustainability is closely linked to waste utilization and resource efficiency. The conversion of PKS into briquettes reduces the need for disposal or open burning, thereby mitigating localized air pollution and solid waste accumulation within palm oil mill environments (Nurdin et al., 2025a; Nurdin et al., 2025b). This waste valorization pathway aligns with circular economy principles by reintegrating residues into the energy-value chain. Simultaneously, sustainability assessments must consider the broader palm oil system context. Although PKS briquetting does not drive plantation expansion, upstream land-use practices and environmental pressures associated with the palm oil industry remain relevant to holistic sustainability evaluations (Ming et al., 2024).

From an economic standpoint, PKS briquettes demonstrate a strong techno-economic potential as renewable solid fuels. Their favorable physicochemical properties, including low inherent moisture, moderate ash content, and high calorific values of up to 30.72 MJ/kg, underpin their technical feasibility in industrial boilers, kilns, and small-scale thermal systems (Alfian et al., 2026; Nurdin et al., 2025a; Nurdin et al., 2025b). Process optimization, particularly in terms of densification and binder use, plays a critical role in economic performance. Appropriate control of compaction pressure, particle size, and binder concentration enhances briquette durability and combustion efficiency, thereby reducing breakage losses and improving energy consistency (Bazargan et al., 2018; Salim et al., 2024). Economically, the availability of PKS as a low-cost or negative-cost feedstock in palm oil–producing regions substantially lowers raw material expenses. Techno-economic analyses of PKS-derived briquettes and biochar have reported favorable profit-to-cost ratios when production is integrated with existing palm oil infrastructure (Seow et al., 2024).

Positive economic indicators were also observed at smaller scales. Community- and household-level briquette initiatives based on agricultural residues, including PKS composites, have demonstrated positive net present values and relatively low break-even points, highlighting their relevance for decentralized energy systems and rural development (Kpalo et al., 2022). Market competitiveness is further strengthened by the ability of PKS briquettes to replace fuelwood, charcoal, and even coal in certain applications, offering a higher energy density and reduced pressure on forest resources (Osei Bonsu et al., 2020; Handaya et al., 2024).

Despite these advantages, several challenges constrain their large-scale commercialization. Feedstock supply reliability can be affected by seasonal variations, competing uses, and logistical constraints in collecting PKS from dispersed mills (Handaya et al., 2024). Ensuring consistent quality requires precise control of production parameters, as variations in binder type, binder concentration, and compaction conditions can undermine product uniformity and market confidence (Faisal et al., 2019; Obi, 2015). Therefore, market acceptance and policy support are critical. Supportive renewable energy policies, waste-to-energy incentives, and clear regulatory standards can enhance competitiveness and environmental performance, whereas weak or inconsistent policy frameworks may slow adoption (Silva et al., 2022; Handaya et al., 2024).

Overall, environmental and economic assessments consistently indicate that PKS briquettes offer meaningful advantages over fossil fuels and many alternative biomass fuels, driven by their high calorific value, waste-derived feedstock status, and compatibility with circular economy principles. Realizing these benefits at scale depends on optimized production technologies, reliable supply chains, market acceptance, and supportive policy environments that collectively enable PKS briquettes to contribute effectively to sustainable energy transition.

3.5 Research Gaps and Future Directions

Despite substantial progress in the development and characterization of palm kernel shell (PKS) briquettes, the existing literature reveals several limitations that constrain a comprehensive understanding and large-scale deployment. One of the most prominent gaps lies in the fragmentation of current studies, which often focus on isolated parameters, such as calorific value, mechanical strength, or proximate composition, without integrating these properties into a unified performance framework. Consequently, the relationships between the thermal properties, heat transfer behavior, mechanical durability, and real combustion efficiency remain insufficiently resolved. Many studies have reported favorable laboratory-scale results; however, systematic validation under realistic operating conditions, such as continuous combustion, variable load, or long-term cycling, which are critical for industrial and commercial applications, is lacking.

Another limitation is the lack of standardized testing protocols and reporting practices. Variations in sample preparation, carbonization methods, binder concentrations, and measurement techniques complicate direct comparisons across studies. For example, thermal conductivity and heat transfer efficiency are often inferred indirectly or reported under different moisture and density conditions, which limits their generalizability. Similarly, life cycle and techno-economic assessments frequently rely on site-specific assumptions, system boundaries, or allocation methods, making it difficult to draw robust conclusions regarding the overall sustainability of PKS briquettes relative to other biofuels. These inconsistencies highlight the need for harmonized methodologies that enable meaningful cross-study comparisons and meta-analyses.

Material innovation studies also have notable gaps. While advances in binders, composite formulations, and hybrid biomass systems have been widely explored, most investigations remain empirical and are short-term. The long-term stability of advanced binders, composite interfaces, and hybrid briquettes under repeated thermal cycling, storage, and handling has received limited attention. In addition, emerging concepts such as nano-additives or nanostructure-assisted pretreatments have been largely discussed at a conceptual or proof-of-concept level, with scarce experimental data demonstrating their scalability, cost-effectiveness, and environmental implications. This limits their practical relevance, despite their theoretical potential to enhance heat transfer and combustion performance.

Therefore, future research should prioritize integrated experimental designs that simultaneously evaluate the thermal, mechanical, environmental, and economic performances under realistic conditions. Systematic parametric studies that couple densification variables, binder chemistry, and particle characteristics with heat transfer and combustion behaviors are particularly needed. Long-duration combustion tests and pilot-scale demonstrations would provide critical insights into durability, emission stability, and maintenance requirements. From a sustainability perspective, future life-cycle assessments should adopt standardized system boundaries and include sensitivity analyses to capture uncertainties related to feedstock supply, processing energy, and transportation logistics.

Modeling is another key area for advancement. Current thermal and kinetic models often simplify PKS briquettes as homogeneous materials, neglecting internal heterogeneity, evolving pore structures, and coupled heat and mass transfer during combustion. Multiscale models that integrate microstructural information with kinetic and thermophysical properties would improve the predictive accuracy and support reactor and stove design. Data-driven approaches, including machine learning, also offer promising opportunities to link processing parameters with performance outcomes, provided that sufficiently large and high-quality datasets are generated for training.

Addressing the identified research gaps in PKS briquette development requires a multidisciplinary approach that extends beyond conventional materials and thermal analyses. Collaboration among materials scientists, chemical and mechanical engineers, environmental scientists, and energy policy experts is essential to integrate feedstock characterization, process optimization, emissions control, life cycle assessment, and regulatory frameworks into a unified research agenda. Such interdisciplinary efforts can accelerate the translation of laboratory-scale innovations into practical, scalable energy solutions while ensuring environmental compliance and socioeconomic relevance.

Overall, addressing these research gaps requires closer integration of experimental investigations, modeling, and system-level assessments. By moving beyond isolated property evaluation toward holistic and standardized research frameworks, future studies can more effectively support the optimization, commercialization, and sustainable deployment of PKS briquettes as a renewable solid fuel.

4 Conclusion

This systematic review highlights the strong potential of palm kernel shell (PKS)-based briquettes as renewable solid fuels that support waste valorization, energy security, and sustainability within the palm oil industry. The reviewed literature consistently demonstrates that PKS briquettes possess a high calorific value, favorable thermal stability, and reliable combustion behavior, enabling their use as alternatives to fossil-based solid fuels and lower-grade biomass. These properties are largely attributable to the intrinsic characteristics of PKS and can be further enhanced through appropriate carbonization, densification, and binder-selection processes.

Advances in processing technologies, including optimized compaction pressure, controlled thermal pretreatment, and the use of effective binders, have significantly improved the mechanical durability and thermal performance of PKS briquettes. Composite and hybrid biomass formulations further expand their functional versatility by enabling tailored fuel properties for specific applications. From an environmental perspective, life cycle assessments indicate that PKS briquettes generally offer lower greenhouse gas emissions and meaningful waste reduction benefits compared to fossil fuels and many alternative biomass options, particularly because of their waste-derived nature and high energy density. Economically, the abundance and low cost of PKS underpin favorable techno-economic prospects, particularly when production is integrated with existing palm oil infrastructure.

Despite these advantages, challenges related to standardization, large-scale deployment, and policy support remain unresolved. Addressing these issues through integrated research, technological optimization, and supportive regulatory frameworks is critical. Overall, PKS briquettes represent a viable and sustainable renewable solid fuel with significant potential to contribute to cleaner energy transition and circular bioeconomy strategies. Although significant progress has been made in improving the thermal performance and processing technologies of PKS briquettes, their successful deployment as a sustainable energy solution ultimately depends on the integration of technical, environmental, economic, and policy dimensions. Technical optimization alone is insufficient without the concurrent consideration of emissions control, life cycle environmental impacts, production costs, supply chain reliability, and market competitiveness. Likewise, favorable environmental performance must be supported by economically viable production models and policy frameworks.

Therefore, future advancements in PKS briquette technology require a holistic and interdisciplinary approach that aligns material and process innovations with environmental assessments, techno-economic analyses, and supportive regulatory and incentive mechanisms. Such integrated strategies are essential for facilitating large-scale adoption, enhancing investor and stakeholder confidence, and positioning PKS briquettes as a viable component of sustainable energy transitions and circular economy initiatives in palm oil–producing regions.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this manuscript, the author(s) used ChatGPT to improve the readability and fix grammatical errors. After using this tool/service, the author(s) reviewed and edited the content as needed and took (s) full responsibility for the content of the published article.

Ethics Statement

This study no need ethical clearance.

CRediT Authors Statement

Enda Rasilta Tarigan, Abdul Aziz Rahmansyah, Muhammad Khatami: Conceptualizarion, Writing Original Manuscript, Writing-Review And Editing, Finalization

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