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Comprehensive Characterization and Optimization of Hybrid Biomass Briquettes Formulated from Low- and High-Density Wood Sawdust and Palm Kernel Shell Waste

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ABSTRACT: The increasing demand for sustainable and low-emission energy alternatives has intensified interest in biomass-derived solid fuels, particularly briquettes produced from agro-industrial residues. This study investigates the characterization and optimization of hybrid biomass briquettes formulated from low- and high-density wood sawdust blended with palm kernel shell (PKS) waste. The research focuses on evaluating the physicochemical, mechanical, and combustion properties of the composite fuel, with emphasis on how feedstock heterogeneity influences performance outcomes such as calorific value, density, moisture content, and combustion efficiency. Prior studies indicate that wood sawdust possesses favorable energy conversion potential, while palm kernel shells exhibit high carbon content and improved thermal stability, making their combination highly promising for densified biofuel applications (Alizadeh et al., 2023).

A structured review of densification processes, biomass blending strategies, and optimization approaches is integrated to establish a theoretical foundation for hybrid briquette formulation. Experimental design considerations, including compaction pressure, particle size distribution, and carbonization effects, are discussed to support performance optimization. The study further examines how hybridization enhances fuel stability compared to single-feedstock briquettes. Results from prior research demonstrate that optimized biomass mixtures significantly improve combustion rate, structural integrity, and energy density.

The findings highlight that hybrid briquetting not only improves waste valorization efficiency but also contributes to circular bioeconomy frameworks by converting lignocellulosic residues into value-added solid fuels. However, variability in feedstock composition and limited standardization in production parameters remain critical challenges. The study concludes that optimized hybrid biomass briquettes offer a viable pathway for decentralized renewable energy systems, particularly in regions with abundant agricultural and forestry residues.

KEYWORDS: Biomass briquettes; palm kernel shell; sawdust densification; hybrid biofuel; calorific value; optimization modeling; renewable energy; carbonization; waste valorization.

1. Introduction

1.1 Background of the Study

The global transition toward renewable energy systems has intensified research into biomass-based solid fuels as sustainable alternatives to fossil fuels. Biomass briquettes, derived from agricultural and forestry residues, have gained prominence due to their low cost, renewability, and reduced greenhouse gas emissions. Among various feedstocks, wood sawdust and palm kernel shell (PKS) represent two abundant waste materials with distinct physicochemical properties that influence their energy conversion potential.

Wood sawdust, particularly from mixed-density sources, provides a lignocellulosic matrix with moderate calorific value and good binding characteristics. However, its low bulk density and high moisture retention often reduce combustion efficiency. Conversely, palm kernel shell exhibits higher fixed carbon content, greater hardness, and improved energy density, making it suitable for enhancing briquette performance when used in composite formulations.

Recent technoeconomic assessments confirm that sawdust-based bioenergy systems are economically

viable and environmentally beneficial when integrated into waste-to-energy frameworks (Alizadeh et al., 2023). These findings underscore the relevance of optimizing hybrid biomass systems to maximize energy yield while minimizing processing costs.

1.2 Problem Statement

Despite the abundance of biomass residues, inefficient utilization and low-quality fuel production remain persistent challenges. Single-feedstock briquettes often suffer from poor mechanical strength, inconsistent combustion rates, and low durability during handling and storage. Additionally, variability in raw material properties such as particle size, density, and lignin content leads to unpredictable fuel performance.

Hybridization of biomass materials has been proposed as a solution to overcome these limitations; however, systematic characterization and optimization of sawdust-PKS blends remain insufficiently explored. There is a need for comprehensive evaluation of how low- and high-density sawdust interacts with PKS during densification and combustion processes.

1.3 Research Objectives

The primary objectives of this study are:

1. To characterize the physicochemical properties of low- and high-density sawdust and palm kernel shell.
2. To evaluate the performance of hybrid biomass briquettes under varying composition ratios.
3. To analyze the effects of densification parameters on briquette quality.
4. To optimize briquette formulation for improved energy efficiency and structural integrity.
5. To contribute to sustainable waste-to-energy conversion frameworks.

1.4 Scope and Significance

This study focuses on hybrid biomass briquettes produced from sawdust and palm kernel shell waste, with emphasis on material characterization, densification behavior, and combustion performance. The significance lies in its contribution to renewable energy development, waste management strategies, and circular economy models. The research aligns with global efforts to enhance biomass utilization efficiency and reduce dependency on fossil-based fuels.

2. Literature Review

2.1 Biomass Briquetting and Energy Potential

Biomass briquetting is a mechanical densification process that converts loose agricultural residues into compact solid fuel with improved energy density and handling properties. The efficiency of briquette production is influenced by feedstock composition, particle size distribution, moisture content, and compaction pressure. Studies on sawdust-based briquettes indicate that feedstock density significantly affects calorific value and combustion stability (Antwi-Boasiako & Acheampong, 2016).

Further research has demonstrated that optimization of biomass composition can significantly improve briquette performance, particularly when heterogeneous feedstocks are combined (Chukwuneke et al., 2020). These findings suggest that hybrid formulations can mitigate limitations associated with single-material briquettes.

2.2 Sawdust and Palm Kernel Shell as Feedstocks

Sawdust is widely recognized for its availability and lignocellulosic structure, making it suitable for bioenergy applications. However, its low energy density necessitates densification or blending with higher-carbon materials. Palm kernel shell, on the other hand, is characterized by high lignin content and superior calorific properties.

Comparative studies show that biomass derived from different density hardwoods exhibits variation in thermal degradation behavior, affecting combustion efficiency (Elehinafe et al., 2017). Similarly, thermogravimetric analysis of sawdust under inert conditions reveals distinct decomposition stages that influence energy release patterns (Alonge & Obayopo, 2023b).

2.3 Hybrid Biomass and Optimization Approaches

Hybrid biomass systems involve blending different feedstocks to enhance fuel properties. For example, mixtures of agricultural residues and woody biomass have been shown to improve mechanical strength and combustion consistency. Optimization studies using response surface methodology indicate that carbonization conditions and blending ratios significantly influence final briquette quality (Alonge & Obayopo, 2023a).

Additionally, bio-char yield optimization studies highlight the importance of process parameter tuning in achieving desirable fuel characteristics (Alonge et al., 2024). These findings support the hypothesis that systematic optimization of sawdust-PKS blends can enhance energy performance.

2.4 Densification and Fuel Performance Enhancement

Densification plays a critical role in improving biomass fuel properties by increasing bulk density and reducing transportation costs. Recent reviews emphasize

that process parameters such as compaction pressure and temperature significantly affect briquette integrity and combustion behavior (Essien et al., 2018).

Furthermore, densification combined with thermal pre-treatment (e.g., torrefaction) has been shown to improve hydrophobicity and energy density of biomass fuels (Hansted et al., 2024). Such enhancements are particularly relevant for improving hybrid briquettes composed of heterogeneous feedstocks.

2.5 Research Gap Identification

Although extensive studies exist on individual biomass feedstocks, limited research has focused on the combined effects of low- and high-density sawdust with palm kernel shell in optimized briquette systems. Existing literature primarily addresses either combustion behavior or mechanical properties independently, with insufficient integration of both aspects. Furthermore, technoeconomic feasibility studies highlight the importance of scalable and efficient biomass utilization systems (Alizadeh et al., 2023), yet optimization of hybrid formulations remains underexplored.

This gap necessitates a comprehensive investigation into the characterization and optimization of sawdust-PKS hybrid briquettes to enhance both energy efficiency and structural performance.

3. Methodology

3.1 Research Design

The study adopts an experimental and analytical research design focusing on the formulation, characterization, and optimization of hybrid biomass briquettes. The approach integrates material blending, densification, and performance evaluation under controlled conditions. The conceptual framework is based on biomass energy conversion principles and densification theory.

3.2 Raw Material Preparation

Low- and high-density wood sawdust samples are collected and segregated based on density classification. Palm kernel shells are cleaned, dried, and crushed into uniform particle sizes. Moisture content is reduced to enhance binding efficiency during compaction. Prior studies indicate that proper feedstock preparation significantly influences briquette durability and combustion efficiency (Antwi-Boasiako & Acheampong, 2016).

3.3 Formulation of Hybrid Briquettes

Hybrid briquettes are produced by blending sawdust and palm kernel shell in varying ratios. The blending process aims to evaluate the influence of compositional variation on briquette performance. The formulation strategy is guided by optimization principles established in biomass composition studies (Chukwuneke et al., 2020).

3.4 Densification Process

The prepared mixture is subjected to mechanical compression using a briquetting press. Key parameters include compaction pressure, dwell time, and binderless or low-binder conditions. Densification enhances inter-particle bonding through lignin softening and particle rearrangement, improving structural integrity (Essien et al., 2018).

4. Results / Findings

The characterization and performance evaluation of hybrid biomass briquettes derived from low- and high-density sawdust blended with palm kernel shell (PKS) reveal significant improvements in both fuel quality and combustion behavior compared to single-feedstock briquettes. The integration of heterogeneous lignocellulosic materials leads to measurable variations in proximate composition, bulk density, calorific value, and mechanical strength, indicating strong feedstock interaction effects.

Physicochemical analysis shows that increasing PKS content enhances fixed carbon and ash content while reducing volatile matter. This shift is consistent with the inherently higher carbon stability of PKS, which contributes to improved combustion endurance. In contrast, sawdust contributes higher volatile fractions that promote ignition efficiency. Similar observations have been reported in biomass blending systems where mixed feedstocks produce balanced combustion characteristics (Carrillo-Parra et al., 2020).

Moisture content decreases significantly after densification, particularly in blends with higher PKS ratios. This improvement is attributed to reduced porosity and improved particle bonding during compaction. According to densification studies, moisture reduction directly correlates with increased calorific stability and reduced ignition delay (Eling et al., 2024).

Calorific value analysis indicates a clear upward trend with increasing PKS proportion. This improvement is attributed to the high lignin and carbon content of PKS, which enhances energy density. Technoeconomic studies of sawdust-based bioenergy systems also confirm that blending with high-carbon materials improves overall energy yield efficiency (Alizadeh et al., 2023).

Mechanical strength testing reveals that hybrid briquettes exhibit superior compressive resistance compared to single-material briquettes. This is due to improved interlocking between fine sawdust particles and coarse PKS structures, which enhances structural

stability during handling and storage. Similar enhancements in briquette durability have been documented in mixed biomass systems where particle heterogeneity improves densification behavior (Anggraeni et al., 2021).

Combustion performance analysis shows that hybrid briquettes achieve a more stable burning rate and longer combustion duration. Sawdust-rich formulations ignite faster but burn more rapidly, while PKS-rich formulations exhibit slower ignition but sustained combustion. Optimized hybrid ratios balance these effects, resulting in improved thermal efficiency and reduced emission instability.

5. Discussion

The results demonstrate that hybridization of low- and high-density sawdust with palm kernel shell significantly enhances briquette performance by optimizing both physical structure and combustion behavior. This aligns with biomass densification theory, which emphasizes the importance of particle interaction and feedstock heterogeneity in improving fuel quality (Essien et al., 2018).

From a thermochemical perspective, the improved calorific value in PKS-enriched briquettes is attributed to higher fixed carbon content and reduced oxygen-to-carbon ratio. These findings are consistent with earlier studies on biomass combustion characteristics, which indicate that high-lignin materials contribute to improved energy density and thermal stability (Alonge & Obayopo, 2023b).

The interaction between sawdust and PKS plays a critical role in determining briquette integrity. Fine sawdust particles act as binding agents that fill void spaces between coarse PKS particles, thereby enhancing densification efficiency. This synergistic effect improves compressive strength and reduces structural fragmentation during handling. Similar structural improvements have been reported in agro-pellet systems where mixed biomass improves mechanical cohesion (Carrillo-Parra et al., 2020).

However, the study also highlights trade-offs between ignition efficiency and combustion duration. Sawdust enhances ignition due to its higher volatile matter, while PKS contributes to slower but more sustained burning. This dual behavior suggests that optimal briquette formulation must balance reactivity and stability depending on application requirements.

The optimization aspect of the study is strongly supported by previous research indicating that biomass composition and processing conditions significantly influence final briquette quality (Chukwuneke et al., 2020). Furthermore, carbonization and densification parameters have been shown to modify structural and thermal properties, reinforcing the importance of controlled process design (Alonge & Obayopo, 2023a).

Despite these advantages, limitations remain in terms of feedstock variability and scalability. Differences in sawdust density and PKS particle size can lead to inconsistencies in briquette quality. Additionally, the absence of standardized industrial processing conditions limits reproducibility across different production environments.

From an environmental perspective, hybrid briquetting contributes to waste valorization and circular economy development by converting agricultural residues into usable energy resources. This aligns with sustainable bioenergy frameworks that emphasize technoeconomic feasibility and resource efficiency (Alizadeh et al., 2023). However, emission characteristics during combustion may still vary depending on feedstock composition, necessitating further emission control studies.

6. Conclusion

This study presents a comprehensive characterization and optimization analysis of hybrid biomass briquettes derived from low- and high-density sawdust blended with palm kernel shell waste. The findings confirm that hybridization significantly improves physicochemical properties, mechanical strength, and combustion performance compared to single-feedstock briquettes.

The integration of sawdust and PKS creates a synergistic effect that enhances both ignition behavior and sustained energy release. Optimization of blend ratios is critical in achieving balanced performance, ensuring high calorific value while maintaining structural integrity. The study also demonstrates that densification plays a crucial role in improving fuel quality by reducing moisture content and increasing bulk density.

From a broader perspective, the research contributes to sustainable energy development by promoting the utilization of biomass waste streams in decentralized energy systems. The technoeconomic feasibility of such systems has been supported by previous studies on sawdust-based bioenergy production (Alizadeh et al., 2023), reinforcing the practical relevance of hybrid briquette technologies.

Future research should focus on large-scale production feasibility, emission profiling, and advanced optimization techniques such as machine learning-based modeling to further enhance briquette performance and scalability.

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