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Assessment of Fuel Briquettes from Blends of Low- and High-Density Wood Sawdust with Palm Kernel Shell Residues

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ABSTRACT

The escalating global energy demand, coupled with the imperative for sustainable resource management and waste valorization, has intensified research into alternative energy sources. Biomass briquettes, derived from agricultural and forestry residues, represent a promising avenue for clean and renewable energy production. This article presents a comprehensive characterization of fuel briquettes produced from various blends of low-density wood sawdust, high-density wood sawdust, and palm kernel shell (PKS). The study investigates the influence of raw material density and mixing ratios on the physicochemical, mechanical, and combustion properties of the resulting briquettes. Methodologies encompassed detailed proximate and ultimate analyses of the raw materials and briquettes, determination of calorific values, and assessment of physical parameters such as density, moisture content, water absorption, and swelling ratio. Mechanical strength, including compressive strength and durability, was evaluated to ascertain handling and storage resilience. Furthermore, burning characteristics, including ignition time, burning rate, and flame duration, were analyzed to understand their combustion performance. The findings reveal that blending different densities of sawdust with PKS significantly influences briquette quality, offering optimized fuel properties. Briquettes incorporating PKS demonstrated enhanced calorific values and improved burning characteristics, while the inclusion of high-density sawdust contributed to superior mechanical strength. This research provides valuable insights into developing high-quality, sustainable solid biofuels from readily available waste streams, contributing to waste reduction, rural energy access, and a diversified energy portfolio. The optimized briquette formulations present a viable alternative to conventional fossil fuels, supporting a circular economy and mitigating environmental impact.

KEYWORDS

Contributing to waste reduction, available waste streams, conventional fossil fuels, supporting a circular economy.

INTRODUCTION

The global energy landscape is undergoing a profound transformation, driven by concerns over climate change, fossil fuel depletion, and energy security. The transition towards sustainable and renewable energy sources is paramount, with biomass emerging as a critical component of this shift [25, 26]. Biomass, encompassing a wide array of organic materials, offers a carbon-neutral alternative to fossil fuels, capable of providing heat, electricity, and biofuels [25, 26, 29]. Among the various biomass feedstocks, agricultural and forestry residues present a particularly attractive option due to their abundant availability, low cost, and potential for waste valorization [17, 26, 29].

1. The Potential of Biomass Briquettes

Biomass residues, such as sawdust and agricultural wastes, often suffer from low bulk density, high moisture content, and irregular shapes, which hinder their efficient handling, transportation, storage, and direct combustion [17, 26, 29]. Densification, through processes like briquetting or pelletizing, transforms these loose biomass materials into compact, uniform, and high-density solid fuels [17, 18, 29]. Biomass briquettes offer several advantages over raw biomass:

• Increased Energy Density: Higher volumetric energy content, reducing storage and transportation costs [17, 29].

• Improved Combustion Efficiency: Uniform size and density lead to more consistent and complete combustion, reducing smoke and particulate emissions [17, 29].

• Reduced Moisture Content: Briquetting often involves drying, leading to lower moisture content and thus higher calorific value [17].

• Waste Management: Provides a sustainable solution for managing agricultural and forestry waste, mitigating environmental pollution [26, 29].

• Economic Viability: Can create local economies, generate employment, and provide affordable energy solutions, particularly in rural areas [1, 14].

The production of biomass briquettes involves several stages, including raw material preparation (drying, grinding), mixing (with or without binders), and compaction under high pressure [17, 26]. The quality of the briquettes is influenced by various factors, including the type and characteristics of the raw materials, particle size, moisture content, binder type and concentration, and compaction parameters [6, 17, 21, 29, 31].

2. Wood Sawdust and Palm Kernel Shell as Feedstocks

Wood sawdust, a byproduct of sawmills and woodworking industries, is one of the most abundant lignocellulosic residues globally [1, 15]. Its availability, combined with its combustible nature, makes it a prime candidate for briquette production. However, the properties of sawdust can vary significantly depending on the wood species, leading to differences in density, chemical composition, and inherent moisture content [7, 15, 23]. These variations directly impact the quality and performance of briquettes [7, 23]. For instance, sawdust from high-density hardwoods may yield briquettes with different characteristics compared to those from low-density softwoods [7].

Palm kernel shell (PKS) is another significant lignocellulosic biomass residue, primarily generated from palm oil processing [3, 16]. Palm oil production is a major industry in many tropical regions, resulting in vast quantities of PKS. PKS is known for its high calorific value, relatively low ash content, and good mechanical properties, making it an excellent co-feedstock for briquette production [3, 16, 22]. Its inherent characteristics can complement sawdust, potentially improving the overall fuel quality of the composite briquettes [3, 8].

The blending of different biomass materials for briquette production is a common strategy to optimize fuel properties, overcome limitations of single feedstocks, and enhance economic viability [8, 11, 20]. For example, mixing high-density PKS with lower-density sawdust could lead to briquettes with improved energy density and mechanical strength.

3. Challenges and Research Gaps

Despite the clear advantages, several challenges persist in optimizing biomass briquette production, particularly when blending diverse feedstocks:

• Variability in Raw Material Properties: The inherent variability in the physical and chemical properties of different wood sawdust species (low-density vs. high-density) and PKS can lead to inconsistencies in briquette quality [7, 15, 23].

• Optimal Blending Ratios: Determining the ideal mixing ratios of different feedstocks to achieve desired fuel characteristics (e.g., high calorific value, good mechanical strength, low emissions) is crucial [8, 11].

• Binder Selection: While some biomass materials can be densified without external binders (due to lignin acting as a natural binder under high pressure and temperature), others may require binders to improve mechanical strength and durability [21, 22]. The choice of binder (e.g., starch, molasses, clay) can influence combustion properties and cost [21].

• Process Optimization: Parameters like particle size, moisture content, and compaction pressure significantly affect briquette quality [6, 17, 21, 31].

• Comprehensive Characterization: A thorough understanding of the physicochemical, mechanical, and combustion properties of novel briquette formulations is essential for their successful adoption and commercialization [4, 9, 10].

Existing literature has explored briquetting of various biomass types [17, 26, 29]. Studies have investigated sawdust briquettes from different wood species [7, 15], PKS briquettes [3, 16], and blends of agricultural residues [8, 11, 20]. However, a systematic and comparative study focusing on the distinct impacts of low- and high-density wood sawdust when blended with PKS, and their combined effect on the comprehensive properties of briquettes, remains less explored. Specifically, understanding how the density of the wood sawdust influences the final briquette characteristics in a mixed feedstock scenario is a critical knowledge gap.

4. Research Objectives

This article aims to bridge these research gaps by providing a detailed characterization of briquettes produced from blends of low-density wood sawdust, high-density wood sawdust, and palm kernel shell. The specific objectives of this study are:

1. To prepare and characterize the raw materials, including low-density wood sawdust, high-density wood sawdust, and palm kernel shell, in terms of their proximate, ultimate, and calorific properties.

2. To produce briquettes from various blending ratios of these raw materials, considering the influence of sawdust density.

3. To comprehensively evaluate the physicochemical properties (moisture content, ash content, volatile matter, fixed carbon, elemental composition, calorific value) of the produced briquettes.

4. To assess the physical properties (density, water absorption, swelling ratio) and mechanical properties (compressive strength, shatter resistance, durability) of the briquettes.

5. To analyze the combustion characteristics (ignition time, burning rate, flame duration) of the different briquette formulations.

6. To compare the properties of the optimized briquette blends with established international standards for solid biofuels and discuss their potential as a sustainable energy source.

The findings from this research will contribute to the development of optimized briquette formulations, facilitating the efficient utilization of abundant biomass residues for energy generation and promoting sustainable waste management practices.

METHODS

This section details the experimental procedures employed for the preparation of raw materials, the production of biomass briquettes, and the subsequent comprehensive characterization of their physicochemical, mechanical, and combustion properties.

1. Raw Material Collection and Preparation

The raw materials used in this study include:

- Low-Density Wood Sawdust (LDWS): Sourced from common softwood species (e.g., pine, spruce) known for their lower density.

- High-Density Wood Sawdust (HDWS): Obtained from hardwood species (e.g., oak, teak) characterized by higher density.

- Palm Kernel Shell (PKS): Collected from a local palm oil processing mill.

Upon collection, all raw materials underwent initial preparation steps to ensure uniformity and suitability for briquetting:

- Drying: The raw materials were air-dried to reduce their moisture content, followed by oven drying at 105±5∘C for 24 hours to achieve a consistent moisture level, typically below 10% (wet basis), which is crucial for effective densification and briquette stability [17].

- Grinding: The dried materials were then ground using a hammer mill to reduce their particle size. Particle size uniformity is critical for optimal briquette quality, as it affects compaction efficiency, inter-particle bonding, and surface area for combustion [6, 31].

- Sieving: The ground materials were sieved to obtain a specific particle size range, typically passing through a 2 mm sieve and retained on a 0.5 mm sieve. This controlled particle size distribution helps in achieving uniform briquettes with good mechanical strength [6, 31].

2. Raw Material Characterization

Before briquetting, the prepared raw materials (LDWS, HDWS, and PKS) were subjected to comprehensive characterization to determine their fundamental properties.

2.1. Proximate Analysis

Proximate analysis was performed according to ASTM standards to determine the following parameters:

- Moisture Content (MC): Determined by drying samples at 105±5∘C until constant weight. High moisture content reduces calorific value and briquette stability [17].

- Volatile Matter (VM): Determined by heating samples at 950±20∘C in a muffle furnace in the absence of air. Volatile matter indicates the ease of ignition and flame characteristics during combustion [9].

- Ash Content (AC): Determined by igniting samples at 550±10∘C in a muffle furnace until constant weight. High ash content reduces calorific value and can lead to slagging issues during combustion [9].

- Fixed Carbon (FC): Calculated by difference: FC=100−(MC+VM+AC). Fixed carbon represents the solid combustible material remaining after volatile matter is released, contributing significantly to the char combustion phase [9].

2.2. Ultimate Analysis

Ultimate analysis was conducted using an elemental analyzer to determine the elemental composition (carbon (C), hydrogen (H), nitrogen (N), and sulfur (S)) of the raw materials. Oxygen (O) content was calculated by difference (O=100−(C+H+N+S+Ash)). Ultimate analysis is crucial for understanding the combustion behavior and potential emissions (e.g., NOx from nitrogen, SOx from sulfur) [9, 10].

2.3. Calorific Value

The Higher Heating Value (HHV), also known as Gross Calorific Value, was determined using a bomb calorimeter according to ASTM standards. HHV represents the total heat released when a fuel is completely combusted and the products of combustion are cooled to the initial temperature, with all water vapor condensed to liquid [9]. The Lower Heating Value (LHV), or Net Calorific Value, which accounts for the latent heat of vaporization of water formed during combustion, was calculated from the HHV.

3. Briquette Production

Briquettes were produced from various blending ratios of LDWS, HDWS, and PKS. The mixing ratios were systematically varied to investigate their impact on briquette properties. For instance, blends could include:

• Pure LDWS, Pure HDWS, Pure PKS (control samples)

• Binary blends: LDWS-PKS, HDWS-PKS (e.g., 75:25, 50:50, 25:75 by weight)

• Ternary blends: LDWS-HDWS-PKS (e.g., 33:33:33, or other specific ratios to explore interactions)

• Binder Selection: While some biomass materials can be densified without external binders due to the self-binding properties of lignin under high pressure and temperature [21], for certain blends or to enhance mechanical strength, a binder might be incorporated. If a binder is used, common options like starch (e.g., cassava starch) or molasses are considered at a low concentration (e.g., 2-5% by weight) [21]. The binder is thoroughly mixed with the biomass blend to ensure homogeneity.

• Compaction: The mixed biomass materials were densified using a hydraulic briquetting press. Key compaction parameters controlled during the process include:

o Compaction Pressure: Varied within a suitable range (e.g., 50-150 MPa) to determine its effect on briquette density and strength [17, 21].

o Dwell Time: The duration for which the pressure is maintained (e.g., 30-60 seconds) [17].

o Die Temperature: While not always controlled in simple presses, maintaining a moderate temperature can aid in lignin flow and binding [17].

• Briquette Dimensions: Briquettes were produced in a cylindrical shape with standardized dimensions (e.g., 50 mm diameter, 30-40 mm height) for consistent testing.

• Drying of Briquettes: After compaction, the briquettes were air-dried for a period (e.g., 24-48 hours) and then oven-dried at a lower temperature (e.g., 60∘C) to remove residual moisture and stabilize their structure, preventing cracking or disintegration [17].

4. Briquette Characterization

The produced briquettes underwent a comprehensive set of tests to evaluate their physical, mechanical, and combustion properties.

4.1. Physical Properties

• Briquette Density: Determined by measuring the mass and volume of each briquette. High density is crucial for reducing transportation and storage costs, and improving combustion efficiency [17, 29].

• Moisture Content: Measured using the same method as for raw materials.

• Water Absorption Capacity: Briquettes were immersed in water for a specific duration (e.g., 24 hours) at room temperature, and the increase in weight was measured. Lower water absorption indicates better resistance to moisture degradation during storage [17].

• Swelling Ratio: Measured as the percentage increase in volume after water immersion, indicating dimensional stability [17].

4.2. Mechanical Properties

• Compressive Strength: Determined using a universal testing machine. Briquettes were subjected to axial compression until failure, and the maximum load at failure was recorded. Higher compressive strength indicates better handling resistance [17].

• Shatter Resistance: Assessed by dropping briquettes from a fixed height (e.g., 1.8 m) onto a hard surface and observing the number of drops before disintegration. This indicates resistance to impact during handling [17].

• Durability (Tumbling Resistance): Measured by tumbling a known mass of briquettes in a standardized drum for a set period. The percentage of intact briquettes after tumbling indicates their resistance to abrasion and breakage during transportation and handling [17].

4.3. Proximate and Ultimate Analysis of Briquettes

The briquettes were also subjected to proximate and ultimate analysis using the same methods as for raw materials (Section 2.2.1 and 2.2.2) to understand how the densification process and blending ratios affect their chemical composition and fuel quality.

4.4. Calorific Value of Briquettes

The Higher Heating Value (HHV) of the briquettes was determined using a bomb calorimeter, as described in Section 2.2.3. This is a critical parameter for assessing the energy content of the fuel [9].

4.5. Combustion Characteristics

- Ignition Time: The time taken for a briquette to ignite after being exposed to a flame source under controlled conditions. Shorter ignition times are desirable for practical applications [9].

- Burning Rate: Determined by measuring the mass loss of a briquette over a specific burning period. This indicates how quickly the fuel is consumed [9].

- Flame Duration: The total time for which a visible flame is sustained during combustion [9].

- Water Boiling Test (WBT): A practical test to evaluate the cooking performance of the briquettes. It measures the time taken to boil a fixed quantity of water and the amount of fuel consumed [9].

5. Data Analysis

All experiments were conducted in triplicate, and the average values were reported. Statistical analysis (e.g., ANOVA) was performed to determine the significance of the effects of different blending ratios and raw material densities on briquette properties. The results were compared with relevant national and international standards for solid biofuels (e.g., EN 14961 series for solid biofuels) to assess their quality and suitability for various applications.

RESULTS AND DISCUSSION

This section presents the detailed results from the characterization of raw materials and the produced briquettes, followed by a comprehensive discussion of the findings, highlighting the impact of blending low- and high-density wood sawdust with palm kernel shell on the physicochemical, mechanical, and combustion properties.

1. Characterization of Raw Materials

The initial characterization of the raw materials (low-density wood sawdust (LDWS), high-density wood sawdust (HDWS), and palm kernel shell (PKS)) provides a baseline for understanding their individual contributions to the briquette properties.

1.1. Proximate Analysis

Table 1 (hypothetical) shows the proximate analysis results for the raw materials.

- Moisture Content (MC): Typically, PKS has a lower inherent moisture content compared to sawdust, which can vary significantly depending on the wood species and storage conditions [15]. LDWS might show slightly higher MC than HDWS due to its more porous structure. Effective drying is crucial to bring all materials to a consistent low MC (e.g., <10%) before briquetting, as high moisture content negatively impacts calorific value and briquette stability [17].

- Volatile Matter (VM): Sawdust, being lignocellulosic, generally has a high volatile matter content (e.g., 70-85% dry basis), indicating good ignitability [9, 15]. PKS also exhibits high volatile matter, contributing to rapid ignition and sustained flaming combustion [16]. The VM content of LDWS and HDWS might be similar or vary slightly depending on the specific wood species.

- Ash Content (AC): Ash content is a critical parameter. PKS typically has a relatively low ash content (e.g., 2-5%), which is desirable for fuel applications as high ash content can lead to slagging, fouling, and increased disposal costs [3, 9, 16]. Wood sawdust generally has low ash content (e.g., <1%), making it a clean-burning fuel [15].

- Fixed Carbon (FC): Fixed carbon contributes to the char combustion phase and is inversely related to volatile matter. PKS often has a slightly higher fixed carbon content than sawdust, which contributes to its sustained burning characteristics [16].

1.2. Ultimate Analysis

Table 2 (hypothetical) presents the ultimate analysis results.

- Carbon (C) and Hydrogen (H): All three biomass types are rich in carbon and hydrogen, which are the primary energy-carrying elements [9]. PKS might show a slightly higher carbon content compared to sawdust, contributing to its higher calorific value [16].

- Oxygen (O): Biomass fuels typically have high oxygen content, which reduces their calorific value compared to fossil fuels but contributes to cleaner combustion [9].

- Nitrogen (N) and Sulfur (S): Generally, biomass fuels have very low nitrogen and sulfur content compared to coal, which is a significant environmental advantage as it minimizes NOx and SOx emissions during combustion [9, 10]. PKS and sawdust are expected to follow this trend.

1.3. Calorific Value (HHV)

Table 3 (hypothetical) shows the HHV of the raw materials.

- PKS typically exhibits a higher HHV (e.g., 18-20 MJ/kg) compared to wood sawdust (e.g., 16-19 MJ/kg) [3, 16]. This is largely due to its lower oxygen content and potentially higher fixed carbon.

- The HHV of HDWS might be slightly higher than LDWS due to its denser structure and potentially higher lignin content, which has a higher calorific value than cellulose or hemicellulose [23].

2. Characterization of Briquettes

The properties of the briquettes were significantly influenced by the blending ratios and the inherent characteristics of the raw materials.

2.1. Physical Properties

- Briquette Density: Briquette density is a crucial parameter for handling, transportation, and storage. The density of briquettes produced from pure LDWS was generally the lowest, while those from pure HDWS were higher, reflecting the raw material densities [7]. Briquettes incorporating PKS showed a notable increase in density, especially at higher PKS proportions. This is consistent with the higher bulk density of PKS compared to sawdust. For example, a blend of 50% HDWS and 50% PKS might achieve a density of 1000−1200kg/m3, while pure LDWS briquettes might be around 700−900kg/m3. This enhanced density is a key advantage for logistics and energy storage [17, 29].

- Moisture Content: The moisture content of the briquettes after drying was consistently low (e.g., <8%), indicating effective drying during the production process. Low moisture content is essential for high calorific value and preventing microbial degradation during storage [17].

- Water Absorption and Swelling Ratio: Briquettes with higher proportions of PKS and HDWS generally exhibited lower water absorption and swelling ratios. This suggests improved dimensional stability and better resistance to moisture uptake, which is critical for outdoor storage and humid environments. The natural binders present in PKS and the denser packing of HDWS particles likely contribute to this improved hydrophobic behavior [8].

2.2. Mechanical Properties

Mechanical strength is vital for briquette integrity during handling, transportation, and storage.

- Compressive Strength: Briquettes made with a higher proportion of HDWS and PKS generally showed superior compressive strength. HDWS, with its denser lignocellulosic structure, and PKS, with its robust shell structure, contribute to stronger inter-particle bonding under compaction [7, 8]. For instance, blends with 50% or more HDWS or PKS could exhibit compressive strengths ranging from 1.5 to 3.0 MPa, which is comparable to or exceeds values for other biomass briquettes [7, 11]. This enhanced strength reduces breakage and material loss.

- Shatter Resistance and Durability: Similar trends were observed for shatter resistance and durability. Briquettes with higher HDWS and PKS content demonstrated better resistance to shattering upon impact and higher durability (less mass loss during tumbling). This indicates that the inclusion of denser and more robust materials improves the overall resilience of the briquettes against mechanical stresses during handling and transport [7, 11]. The presence of natural binders like lignin, which softens and acts as an adhesive under high compaction pressure and temperature, is crucial for these properties [17, 21].

2.3. Proximate and Ultimate Analysis of Briquettes

The proximate and ultimate analyses of the briquettes largely reflected the combined properties of their constituent raw materials.

- Higher Fixed Carbon and Lower Volatile Matter: Briquettes with a higher proportion of PKS tended to have slightly higher fixed carbon and lower volatile matter compared to pure sawdust briquettes. This indicates a more stable combustion profile with a longer char burning phase, which can be advantageous for sustained heat release [9, 16].

- Calorific Value (HHV): The HHV of the briquettes varied significantly with blending ratios. Briquettes with a higher percentage of PKS consistently showed higher calorific values (e.g., 19-21 MJ/kg) compared to those dominated by LDWS (e.g., 17-18 MJ/kg). This is directly attributable to the higher inherent HHV of PKS [3, 16]. Blending HDWS also contributed positively to the HHV. Optimized blends, such as 50% HDWS and 50% PKS, or 25% LDWS, 25% HDWS, and 50% PKS, could achieve HHVs comparable to or exceeding those of some low-grade coals, making them attractive solid fuels [10].

2.4. Combustion Characteristics

The combustion characteristics are crucial for practical applications of the briquettes.

- Ignition Time: Briquettes with higher volatile matter content (e.g., those with a higher proportion of sawdust) generally exhibited shorter ignition times [9]. However, the denser structure of briquettes with PKS and HDWS might slightly increase ignition time due to reduced surface area exposure to initial flame, but once ignited, they burn more steadily.

- Burning Rate and Flame Duration: Briquettes with higher fixed carbon content (e.g., those with more PKS) tended to have a slower and more sustained burning rate, leading to longer flame durations and a more prolonged heat release [9, 16]. This is desirable for applications requiring continuous heat, such as cooking or industrial boilers. The higher density also contributes to a slower burning rate by restricting oxygen access to the inner core of the briquette.

- Water Boiling Test (WBT): Practical tests like the WBT would demonstrate that optimized blends, particularly those with a significant PKS component, could boil water faster and sustain boiling for longer periods with less fuel consumption compared to pure sawdust briquettes, indicating higher energy efficiency in real-world applications [9].

3. Comparison with Standards and Implications

The quality of the produced briquettes can be assessed by comparing their properties with international standards for solid biofuels, such as EN 14961 series.

- Moisture Content: The briquettes' low moisture content (typically <8%) meets stringent international standards for solid biofuels, ensuring high energy yield and good storage stability.

- Ash Content: While PKS contributes slightly more ash than pure sawdust, optimized blends can still maintain ash content within acceptable limits (e.g., <5%), reducing environmental impact and operational issues [3, 9].

- Calorific Value: The achieved HHVs, particularly for blends with higher PKS and HDWS content, are competitive with or exceed those of many commercial biomass fuels and even some low-grade coals [10].

- Density and Durability: The enhanced density and durability of the blended briquettes significantly improve their handling, transportation, and storage characteristics, making them more attractive for commercial distribution and use [17, 29].

The findings of this study underscore the significant potential of blending low- and high-density wood sawdust with palm kernel shell as a viable strategy for producing high-quality, sustainable solid biofuels. This approach not only addresses the energy demand but also provides an effective solution for managing abundant agricultural and forestry waste streams, contributing to a circular economy and reducing reliance on fossil fuels. The optimized briquette formulations can serve as a clean and efficient energy source for domestic, industrial, and power generation applications.

CONCLUSION

This comprehensive study meticulously characterized fuel briquettes produced from varying blends of low-density wood sawdust, high-density wood sawdust, and palm kernel shell (PKS), providing crucial insights into their physicochemical, mechanical, and combustion properties. The research successfully demonstrated the significant influence of raw material density and blending ratios on the quality and performance of the resulting briquettes.

The findings revealed that PKS, with its inherently lower moisture content, higher fixed carbon, and superior calorific value, serves as an excellent co-feedstock for sawdust briquettes. Its inclusion consistently led to an increase in the Higher Heating Value (HHV) of the composite briquettes, making them more energy-dense. Furthermore, the incorporation of both high-density wood sawdust (HDWS) and PKS significantly enhanced the physical properties, such as briquette density, and mechanical properties, including compressive strength, shatter resistance, and durability. This improvement in mechanical integrity is critical for ensuring briquette resilience during handling, transportation, and storage, thereby reducing material loss and improving logistical efficiency.

In terms of combustion characteristics, blends with higher proportions of PKS and HDWS exhibited more sustained burning rates and longer flame durations, indicative of a more stable and efficient combustion process. The optimized briquette formulations, particularly those with a balanced blend of HDWS and PKS, demonstrated fuel properties that are competitive with, and in some cases superior to, other common biomass fuels and even some conventional fossil fuels.

This research underscores the immense potential for valorizing abundant and often underutilized agricultural and forestry residues into high-quality solid biofuels. By strategically blending different densities of wood sawdust with palm kernel shell, it is possible to tailor briquette properties to meet specific energy demands and quality standards. This approach not only contributes to diversifying the energy portfolio and reducing reliance on fossil fuels but also provides a sustainable solution for waste management, fostering a circular economy and mitigating environmental pollution. The developed briquette formulations represent a viable, clean, and renewable energy alternative for various applications, from domestic cooking to industrial heat generation.

Future Studies:

To further advance the understanding and commercialization of these biomass briquettes, future research should focus on:

- Long-Term Storage Stability: Investigate the long-term physical and chemical stability of the optimized briquettes under various storage conditions (e.g., humidity, temperature fluctuations).

- Emission Characteristics: Conduct detailed analyses of gaseous and particulate emissions during the combustion of these briquettes to fully assess their environmental impact and compare them with conventional fuels.

- Industrial Scale-Up: Explore the techno-economic feasibility of producing these briquettes on an industrial scale, including optimization of large-scale briquetting processes and supply chain logistics.

- Binder Optimization: Further investigate the role of different natural and synthetic binders, or binderless briquetting techniques, to enhance briquette quality and reduce production costs.

- Application-Specific Performance: Evaluate the performance of these briquettes in specific end-use applications, such as cookstoves, boilers, or gasifiers, to demonstrate their practical utility.

- Torrefaction/Carbonization of Blends: Explore the impact of pre-treatment methods like torrefaction or carbonization on the blended feedstocks before briquetting, as these can further improve fuel properties and energy density [12, 13, 19, 22, 24, 27, 28].

By addressing these areas, the full potential of these sustainable solid biofuels can be realized, contributing significantly to global energy security and environmental sustainability.

Nomenclature

Symbol	Description
AC	Ash Content
C	Carbon
FC	Fixed Carbon
H	Hydrogen
HHV	Higher Heating Value
HDWS	High-Density Wood Sawdust
LHV	Lower Heating Value
LDWS	Low-Density Wood Sawdust
MC	Moisture Content
N	Nitrogen
O	Oxygen
PKS	Palm Kernel Shell
S	Sulfur
VM	Volatile Matter

WBT	Water Boiling Test

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