Uniosun Journal of Engineering and Environmental Sciences (UJEES), Vol. 8 No. 3, March, 2026
DOI: 10.64980/ujees.v8i1.030 **Adeboye et al.**
Published: March 30, 2026

A REVIEW OF CRITICAL PARAMETERS FOR ENHANCED HIGH-QUALITY BIOMASS BRIQUETTES

B. S. ADEBOYE[1], A.T. OYEWO[2*], F. B. OLATUNJI[3] and O. O. ADETAYO[4]
[1]*Mechanical Engineering Department, Osun State University, Osogbo, Nigeria*

[*]*Corresponding Author: abideen.oyewo@uniosun.edu.ng*

Abstract
Despite the alignment of biomass briquetting with anti-climate change policies and sustainable development, the mass production of homogeneous, high-strength briquettes remain a challenge due to the interplay of feedstock factors (such as physical properties) and process conditions. This review highlights the main parameters that determine briquette quality and compiles current knowledge into a mechanistic framework to explain how each variable affects the performance of the final product. Results of the analysis show that feedstock characteristics are critical—particularly lignin content as a natural thermoplastic binder (acting as both plasticizer and lubricant) and particle size distribution, which affects packing density and potential densification. The synergy among process conditions, including compaction pressure as the main driver for particle rearrangement and temperature activating lignin's glass transition, dominates the bonding mechanisms that determine structural integrity. The review identifies major knowledge gaps, such as the need for predictive models that account for feedstock heterogeneity and the difficulty of extrapolating laboratory observations to continuous industrial processes. This review introduces a novel, molecular-level framework for biomass briquetting that goes beyond recent advances. It proposes targeted strategies to optimize briquetting parameters. Thus, this study offers a new approach to improving biomass densification—an essential pillar of sustainable bioenergy systems.

Keywords
Biomass briquetting, Densification, Lignin binder, Process parameters, Fuel quality

1. INTRODUCTION

The global transition towards renewable energy sources has positioned biomass as a critical alternative to fossil fuels, driven by climate change imperatives and energy security concerns. Biomass, encompassing agricultural residues, forest waste, and organic by-products, offers a carbon-neutral pathway for energy generation while supporting rural economies. However, the direct utilization of raw biomass is severely hampered by its intrinsic physical characteristics, including low bulk density, high moisture content, and irregular morphology. These inherent limitations result in prohibitively high transportation costs, inefficient storage, and challenges in handling using conventional fuel equipment, thereby restricting the widespread adoption of biomass in industrial and large-scale energy applications [1, 2].

Briquetting technology has emerged as the principal solution to overcome these logistical barriers through mechanical densification. The process involves compressing loose biomass residues under high pressure, often with the application of heat or binding agents, to produce solid, uniform, and energy-dense fuel logs. This transformation converts low-value waste materials into a standardized commodity characterized by higher volumetric calorific value, reduced dust formation, uniform combustion properties, and significantly lower transportation costs per unit of energy. Consequently, biomass briquetting has gained prominence as a key enabler of sustainable waste management and circular bioeconomy principles, particularly in regions with abundant agricultural residues [1, 3, 4].

According to Ibitoye, et al. [5] and Bisht, et al. [6]The quality of the resulting briquettes is not inherent to the feedstock but is engineered through precise control of interacting parameters that govern physical, mechanical, and combustion characteristics. High-quality briquettes are defined by high density, which correlates with energy content; durability, indicating resistance to fragmentation during handling; and favorable combustion properties such as high calorific value with low ash content. Achieving these attributes requires understanding the complex bonding mechanisms during densification, including solid bridge formation, van der Waals forces, and mechanical interlocking. The natural components of biomass, particularly lignin, play a crucial role as a thermosetting binder that softens under pressure and temperature, forming durable solid bridges upon cooling that confer structural integrity to the briquette [7, 8].

Despite previous efforts, a significant gap remains in understanding the interdisciplinary and interactive effects of key variables—such as feedstock composition, moisture content, particle size, compaction pressure/yield stress, and temperature. Given that different biomass materials exhibit divergent behavioral responses, parameters proven effective for one feedstock cannot be reliably extended to others, resulting in limited predictive clarity regarding briquette quality. The absence of a comprehensive, mechanistic understanding further impedes the design of efficient processes and their industrial scale-up. To address this gap, the present study introduces a novel, molecular-level framework that integrates the interplay between feedstock properties and process conditions. The objective is to move beyond empirical, feedstock-specific observations toward a predictive and mechanistic model capable of guiding the design of high-performance briquettes from diverse biomass residues—thereby advancing both scientific understanding and practical applicability in sustainable bioenergy systems.

2. FEEDSTOCK CHARACTERISTICS

Feedstock characteristics constitute the foundational parameters that determine the inherent potential of biomass to form high-quality briquettes, establishing the baseline upon which process conditions subsequently act. These characteristics encompass both the chemical composition and physical properties of the raw material, each contributing uniquely to densification behavior and final product quality [9, 10].

2.1. Chemical Composition

The chemical composition of lignocellulosic biomass fundamentally dictates its densification behavior and the resulting quality of briquettes. Biomass primarily consists of three major polymeric components—lignin, cellulose, and hemicellulose—along with minor constituents collectively termed extractives. Each of these components contributes uniquely to the bonding mechanisms that occur during the briquetting process, and understanding their individual and synergistic roles is essential for engineering high-quality solid biofuels. The complex interplay between these constituents determines how particles deform, interlock, and bind under the application of pressure and temperature, ultimately governing the mechanical integrity and durability of the final product [8, 11].

2.1.1. Lignin

Lignin is widely recognized as the most critical component for natural bonding in biomass densification. It is an amorphous, cross-linked polyphenolic polymer that functions as the structural glue within plant cell walls, providing rigidity and resistance against degradation. During briquetting, lignin exhibits thermoplastic behavior, meaning it softens and undergoes glass transition when heated to a specific temperature range, typically between 100°C and 160°C depending on the biomass source and moisture content [11]. Upon reaching its glass transition temperature, lignin transforms from a glassy, rigid state to a rubbery, viscous state, allowing it to flow and spread across the surface of adjacent biomass particles. As the material cools after compression, the lignin hardens and solidifies, forming durable solid bridges that bind particles together and confer significant mechanical strength to the briquette [12]. This mechanism is analogous to the function of synthetic thermosetting polymers and explains why elevated temperatures during briquetting substantially enhance product durability. The lignin content of biomass varies considerably between feedstocks, with woody materials typically containing 25-35% lignin, while agricultural residues such as straw and husks contain lower amounts, often 10-20%, which directly correlates with their densification behavior and the need for higher compaction pressures or supplemental binders [13].

2.1.2. Cellulose

Cellulose, the primary structural component of plant cell walls, consists of linear chains of glucose monomers arranged in crystalline and amorphous regions. Unlike lignin, cellulose does not exhibit thermoplastic behavior under typical briquetting conditions and does not melt or soften. Instead, its role in densification is primarily mechanical and structural. Cellulose microfibrils provide tensile strength and elasticity to individual particles, influencing how they deform and compress under applied pressure [5, 14]. During compaction, cellulose fibers can undergo plastic deformation, particularly in amorphous regions, and contribute to mechanical interlocking as particles are forced into close proximity. The hydrogen bonding capacity of cellulose is also significant; the numerous hydroxyl groups along cellulose chains can form intermolecular hydrogen bonds with adjacent cellulose molecules or with other biomass components when particles are brought into intimate contact under pressure [15]. This hydrogen bonding contributes to the initial green strength of the briquette immediately after compression, before lignin solidification occurs. Furthermore, the fibrous nature of cellulose helps create a entangled network within the briquette matrix, enhancing structural cohesion and resistance to fragmentation [16].

2.1.3. Hemicellulose

As reported by Yan, et al. [17], hemicellulose comprises a heterogeneous group of branched polysaccharides that associate closely with cellulose microfibrils in the plant cell wall. It is amorphous, has a lower degree of polymerization than cellulose, and is more hydrophilic and thermally labile. During briquetting, hemicellulose can undergo softening and degradation at temperatures lower than those required for lignin, typically beginning around 150°C to 180°C [18]. This thermal behavior means that hemicellulose may contribute to early-stage bonding mechanisms, particularly when processing temperatures are elevated. As hemicellulose softens, it can act as an adhesive, coating particles and contributing to solid bridge formation alongside lignin. However, excessive temperatures can lead to hemicellulose degradation, releasing volatile organic compounds and potentially weakening the briquette structure [19]. The hydrophilic nature of hemicellulose also significantly influences moisture sorption characteristics, affecting both the optimal moisture content required for densification and the hygroscopic behavior of the final briquette during storage. High hemicellulose content can increase the equilibrium moisture content of briquettes, potentially compromising durability and calorific value over time [18].

2.1.4. Extractives

Extractives encompass a diverse array of low-molecular-weight organic compounds present in biomass, including fats, waxes, resins, tannins, sugars, starches, and phenolic compounds. Although typically comprising only 2-10% of biomass dry weight, extractives can exert a disproportionate influence on briquetting behavior. During densification, especially at elevated temperatures, certain extractives can melt and migrate to particle surfaces, contributing to solid bridge formation and acting as natural binders [20]. For instance, the resins and terpenes present in softwood species are known to enhance particle bonding when heated, partially explaining why pine and other resinous woods often densify more readily than low-extractive hardwoods. Conversely, waxy extractives found on the surfaces of agricultural residues such as rice husks and wheat straw can create hydrophobic barriers that inhibit intimate particle contact and reduce the effectiveness of both natural and added binders [21]. These surface waxes must often be disrupted through mechanical action or thermal treatment to achieve adequate bonding. Additionally, sugars and starches present in certain biomass types can caramelize under heat, forming additional adhesive bridges, though they may also increase susceptibility to biological degradation during storage [1, 22]. The complex interplay between these extractives and the major cell wall polymers underscores the need for feedstock-specific optimization of briquetting parameters, as the chemical fingerprint of each biomass source uniquely determines its densification behavior and the quality of the resulting fuel. Table 1 highlights the thermal behavior of biomass components and process implications while Figure 1 presents the key quality characteristics of a briquettes.

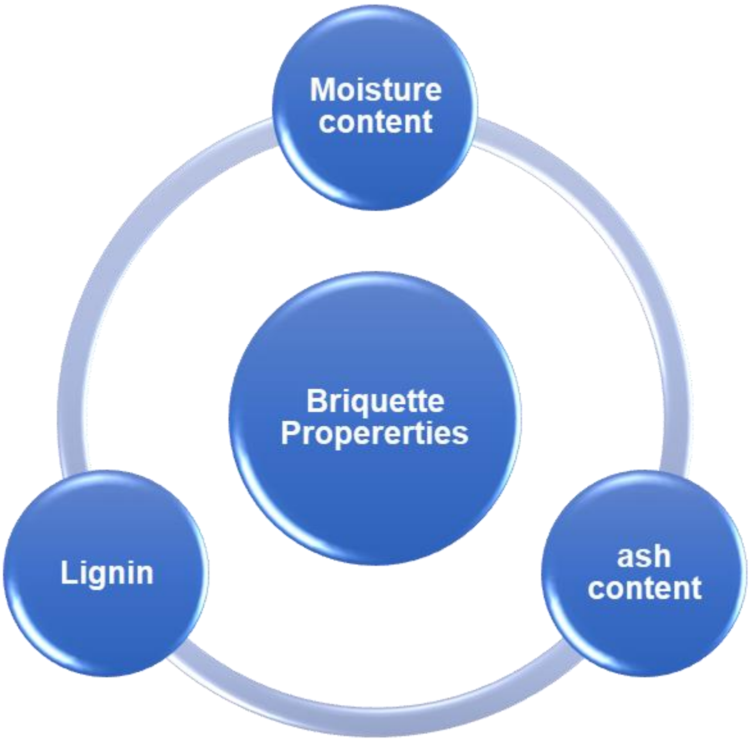

Figure 1: Key quality characteristics of a briquettes [23]

Table 1: Thermal Behavior of Biomass Components and Process Implications [1, 24]

Component	Onset of Softening/Degradation (°C)	Peak Thermal Event (°C)	Process Implication
Lignin	100-120 (softening)	250-450 (degradation)	Optimal binding at 110-160°C; avoid >200°C
Cellulose	250-300 (degradation)	320-360 (degradation)	Stable under typical briquetting temperatures
Hemicellulose	150-180 (softening/degradation)	220-280 (degradation)	Contributes to early bonding; limit to <180°C
Extractives	80-200 (variable)	200-400 (degradation)	Can enhance binding at moderate temperatures

2.2. Moisture Content

Moisture content serves a paradoxical dual function in biomass briquetting, acting simultaneously as both a binding agent and a lubricant during the densification process. As a binder, water facilitates particle cohesion through the formation of hydrogen bonds with the hydroxyl groups present on cellulose, hemicellulose, and lignin surfaces, creating molecular bridges that contribute significantly to the initial green strength of the freshly formed briquette [1, 2]. Furthermore, moisture plasticizes the lignocellulosic structure, lowering the glass transition temperature of lignin and enabling it to soften and flow at lower temperatures, thereby promoting the formation of durable solid bridges upon cooling [25]. Water also serves as a medium for mobilizing soluble extractives such as sugars and starches, which migrate to particle surfaces during compression and precipitate upon drying to form additional solid bridges that augment the binding network. As a lubricant, moisture reduces inter-particle friction and particle-die wall friction, facilitating particle rearrangement, enabling more efficient packing, reducing the energy required for compression, and promoting uniform density distribution throughout the briquette demonstrated that optimal moisture levels could reduce specific energy consumption by 15-25% compared to drier materials, underscoring the economic significance of moisture optimization in industrial operations [20, 25].

Conversely, excessive moisture content introduces equally detrimental effects through entirely different mechanisms. When moisture exceeds the optimal range, excess water occupies volume within the briquette structure and can become pressurized during compression, leading upon rapid pressure release to explosive decompression where superheated water flashes to steam, creating cracks, fissures, and laminations that severely compromise structural integrity [11]. Even when explosive decompression does not occur, excessive moisture prolongs post-production drying time, increases risk of biological degradation during storage, and reduces net calorific value due to the energy penalty of evaporating residual water during combustion. The interaction between moisture and other process parameters adds further complexity, with elevated temperatures partially compensating for suboptimal moisture but higher pressures exacerbating the negative effects of excess water [12]. Ali, et al. [20] proposed that optimal moisture content should be determined as a function of the specific combination of feedstock characteristics, processing conditions, and target specifications, recognizing that even small deviations from the optimal range can have disproportionately large effects on product quality and process economics. This necessitates accurate moisture measurement and control systems in industrial operations, as the narrow optimal window leaves little margin for error.

2.3. Particle Size and Distribution

Particle size and its distribution represent fundamental physical parameters that exert a profound influence on the densification behavior of biomass and the resultant quality attributes of briquettes. The dimensions and size range of feedstock particles govern how they arrange themselves within the compression chamber, the extent of surface area available for bonding interactions, and the mechanical integrity of the final product [1]. Unlike chemical parameters that influence bonding at the molecular level, particle size affects densification through physical mechanisms that determine packing efficiency, stress transmission, and the development of cohesive forces across multiple scales. The intricate relationship between particle characteristics and briquette performance has been extensively investigated, with researchers consistently demonstrating that deliberate manipulation of particle size distribution offers a powerful means of optimizing product quality without altering feedstock chemistry or process conditions [20, 26].

The practical implications of particle size optimization extend beyond the immediate quality attributes of briquettes to encompass process efficiency and economic considerations. Size reduction is an energy-intensive operation, typically accounting for 15-30% of the total energy consumption in a briquetting facility, and the relationship between particle size and energy input is nonlinear, with disproportionately higher requirements for producing very fine materials [20]. This creates an optimization trade-off wherein the benefits of reduced particle size must be balanced against the increased energy costs of achieving that reduction. Wu, et al. [1] reviewed the economic models demonstrating that the optimal particle size distribution from a systems perspective often falls short of the finest possible materials, as the incremental improvements in briquette quality beyond a certain threshold do not justify the additional processing energy. Furthermore, particle shape characteristics interact with size distribution to influence densification outcomes. Fibrous particles with high aspect ratios, typical of many biomass feedstocks, behave differently during compression than equiaxed particles of equivalent nominal dimensions, exhibiting greater propensity for mechanical interlocking but also higher resistance to rearrangement [9]. Gwatidzo, et al. [11] emphasized that particle size specifications must be developed empirically for each feedstock-process combination, as the complex interactions between size, shape, chemical composition, and process conditions preclude the establishment of universal guidelines. This feedstock-specific optimization represents both a challenge and an opportunity, as careful attention to particle size distribution offers one of the most accessible and cost-effective means of enhancing briquette quality without major capital investment or process modification.

3. PROCESS CONDITIONS

Process conditions encompass the mechanical and thermal variables applied during densification that transform loose biomass into coherent briquettes. These parameters govern the extent of particle deformation, activation of natural binders, and development of internal structure that determine final product quality [27].

3.1. Compaction Pressure

Compaction pressure constitutes the fundamental mechanical driving force in biomass briquetting, serving as the primary agent that transforms loose, low-density feedstock into coherent, high-density fuel products. The application of pressure initiates a cascade of physical mechanisms that progressively build briquette structure, beginning with particle rearrangement and sliding as voids are eliminated, followed by elastic and plastic deformation of individual particles, and culminating in the establishment of intimate inter-particle contact necessary for bonding [12]. As pressure increases, particles are forced into closer proximity, reducing the porosity of the compact and enabling the activation of short-range attractive forces such as van der Waals interactions and hydrogen bonding that contribute to cohesion [10]. At sufficiently high pressures, brittle particles may fracture, creating fresh surfaces with high bonding potential, while ductile components undergo plastic flow that fills remaining interstitial spaces and increases the contact area available for solid bridge formation upon cooling. The relationship between applied pressure and achieved density is typically nonlinear, exhibiting an initial region of rapid densification as voids are eliminated, followed by a plateau region where further pressure increases yield diminishing returns as the material approaches its theoretical maximum density [8]. This pressure-density relationship is modulated by feedstock characteristics, with high-lignin materials requiring lower pressures to achieve given densities due to their greater deformability, while fibrous, lignin-poor agricultural residues demand higher compaction forces to achieve comparable results [10]. The practical pressure range for biomass briquetting typically falls between 100 MPa and 200 MPa for piston press technologies, though screw extrusion systems operate at lower pressures due to the additional effects of frictional heating emphasized that a threshold pressure exists for each feedstock below which durable briquettes cannot be formed regardless of other parameter adjustments, while pressures above the optimal range may cause over-compaction, leading to lamination, cracking, or excessive die wear without proportional improvements in product quality. The distribution of pressure within the die is equally important as its magnitude, with uniform pressure transmission throughout the compact being essential for producing homogeneous briquettes free of density gradients and internal stresses that could precipitate failure during handling or storage [11].

3.2. Temperature

Temperature serves as a critical activation parameter in biomass briquetting, fundamentally altering the physical and chemical behavior of feedstock components to facilitate superior bonding and enhance final product quality. The primary role of temperature is to induce thermoplastic transformation in lignin, the natural amorphous polymer that constitutes 15-35% of lignocellulosic biomass, by raising it above its glass transition temperature (Tg), typically between 100°C and 160°C depending on moisture content and feedstock type [2]. Upon reaching Tg, lignin transitions from a rigid, glassy state to a rubbery, viscous condition that enables it to flow under pressure, spreading across particle surfaces and penetrating surface irregularities. As the compressed material cools following ejection from the die, this mobilized lignin solidifies to form durable solid bridges that constitute the primary bonding mechanism in high-quality briquettes [3]. Temperature elevation also softens hemicellulose components and may melt certain extractives such as resins and waxes, contributing additional adhesive phases that augment the lignin-based binding network. Furthermore, elevated temperatures reduce the force required for particle deformation by plasticizing the lignocellulosic matrix, effectively lowering the pressure needed to achieve a given density and thereby reducing energy consumption and die wear [7].

The synergistic interaction between temperature and pressure is particularly significant, as heated particles deform more readily under compression, creating larger contact areas for bonding while the activated lignin simultaneously flows to fill the remaining interfacial gaps. However, the temperature window for optimal briquetting is bounded by upper limits, typically around 200-250°C depending on residence time, beyond which thermal degradation of hemicellulose and eventually cellulose begins, releasing volatile organic compounds, reducing mass yield, and potentially weakening the briquette structure through the formation of fissures from evolved gases [7]. Obernberger and Thek (2004) demonstrated that within the optimal range, even modest temperature increases of 20-30°C can produce durability improvements of 10-15%, underscoring the sensitivity of briquette quality to this parameter and the importance of precise temperature control in industrial operations. The heat source and distribution method also influence outcomes, with friction-based heating in screw extruders producing different temperature profiles and material effects compared to externally heated die systems, necessitating process-specific optimization [9].

3.3. Die Geometry and Retention Time

Die geometry and retention time represent interrelated process parameters that profoundly influence the densification outcome through their effects on pressure distribution, stress relaxation, and the duration of thermal exposure during briquetting. The geometry of the die, particularly its length-to-diameter ratio (L/D), determines how effectively applied pressure is transmitted through the biomass column, with longer dies providing greater frictional resistance that increases the effective pressure experienced by material nearer the die entrance while simultaneously creating a pressure gradient along the die length [25]. This pressure gradient influences density uniformity within the briquette, as material near the die exit typically experiences lower effective pressures than that near the punch, potentially resulting in density variations that can compromise structural integrity and create planes of weakness susceptible to fracture during handling [10].

The die's taper angle, where applicable, affects material flow and the development of lateral stresses that determine the radial pressure distribution and the intensity of frictional heating during extrusion [3]. Extended retention also prolongs thermal exposure, facilitating more complete heat transfer throughout the compact and enabling thorough lignin plasticization, which enhances solid bridge formation upon cooling [25]. However, excessively long retention times reduce production throughput and may cause thermal degradation of heat-sensitive components if temperatures are elevated, necessitating optimization of the pressure-temperature-time relationship for each feedstock-process combination [25]. Lu, et al. [9] demonstrated that for a given feedstock, there exists a critical retention time below which durable briquettes cannot be formed regardless of pressure magnitude, as insufficient time prevents the viscoelastic deformation and molecular rearrangement necessary for stable bond formation. Table 2 provides a comprehensive summary of these process parameters, their typical ranges, effects on briquette quality, and key references from the literature.

4. QUALITY EVALUATION METRICS

Quality evaluation metrics for biomass briquettes encompass the standardized measurements and testing protocols used to assess product performance and determine suitability for various applications. These metrics are broadly categorized into physical, mechanical, and combustion properties, each providing essential information about different aspects of briquette quality and behavior throughout the supply chain from production to end-use [2, 3].

4.1. Physical and Mechanical Properties

Density stands as the most fundamental physical property of biomass briquettes, serving as a direct indicator of densification success and a primary determinant of fuel value. Particle density, typically ranging from 1000 to 1400 kg/m³ for well-densified biomass, represents a four- to tenfold increase over raw feedstock bulk density, and this dramatic densification constitutes the primary economic justification for briquetting [1]. The relationship between density and energy content is commercially significant: higher density briquettes contain more energy per unit volume, enabling more efficient storage, reduced transportation costs per unit of energy delivered, and longer burn times in combustion appliances Song, et al. [25] demonstrated that every 10% increase in briquette density translates to approximately 8-9% reduction in transportation costs on a per-energy basis, underscoring the economic imperative of achieving maximum practical density. Density is governed by the combined effects of feedstock characteristics and process parameters, with particle size distribution, moisture content, compaction pressure, and temperature all exerting significant influence. The theoretical maximum density is determined by the true density of lignocellulosic material, approximately 1500 kg/m³, though practical operations typically achieve 80-90% of this value due to residual porosity and elastic recovery upon pressure release [7]. Table 3 presents durability classifications and their practical implications for handling and storage.

Table 2: Summary of Process Conditions in Biomass Briquetting [9-11]

Parameter	Typical Range	Mechanism of Action	Effect on Briquette Quality	Optimal Consideration
Compaction Pressure	100-200 MPa (piston press); 50-150 MPa (screw extruder)	Particle rearrangement; elastic/plastic deformation; void elimination;	Increases density up to threshold; enhances durability;	Feedstock-dependent; threshold exists below which no durable briquette forms.
Temperature	80-180°C (typical); 100-160°C (lignin Tg range)	Lignin thermoplasticity; hemicellulose softening; extractive melting; reduced deformation resistance	Enhances solid bridge formation; improves durability by 10-15% per 20-30°C increment;	Must reach lignin Tg; avoid >200-250°C to prevent thermal degradation
Die Geometry (L/D Ratio)	3:1 to 8:1 (typical range)	Determines pressure gradient; influences frictional resistance; affects radial stress development	Affects density uniformity; influences surface quality; determines ejection force requirements	Longer L/D increases effective pressure but may create density gradients
Retention Time	1-30 seconds (varies with technology)	Enables stress relaxation; allows creep deformation; facilitates heat transfer	Reduces spring-back effect.	Critical minimum exists for each feedstock;
Pressure-Temperature Interaction	Synergistic within optimal ranges	Heated particles deform more readily; activated lignin flows under pressure;	Enables high durability at lower individual parameter extremes;	Optimization requires simultaneous consideration; cannot optimize in isolation
Pressure Gradient (along die)	Function of L/D ratio and friction coefficient	Creates density variation from die entrance to exit; influences internal stress distribution	May cause lamination or cracking if excessive;	Minimize through optimal L/D and lubrication;
Heating Method	External die heating; frictional heating; steam conditioning	Affects temperature distribution; influences heating rate; determines energy efficiency	Impacts uniformity of lignin activation;	Method selection depends on technology;

Table 3: Durability Classifications and Handling Implications

Durability Class	Durability Value (%)	Handling Characteristics	Storage Behavior	Typical Applications	Reference
Excellent	>97	Resists all handling; minimal fines generation	Stable for years; no degradation	Export; long-term storage; industrial users	[12]
Good	95-97	Withstands mechanical handling; slight fines	Stable for months; minimal caking	Commercial distribution; domestic heating	[12]
Acceptable	90-95	Survives handling with care; some fines	Stable for weeks; may absorb moisture	Local markets; immediate use	[20]
Marginal	85-90	Fragile; significant fines during handling	Degrades during storage; prone to breakage	On-site use only; not transportable	[12]
Poor	<85	Crumbles easily; high dust generation	Rapid degradation; unsaleable	Requires rebriquetting; process failure	[3]

Durability and hardness constitute the mechanical properties that determine briquette resilience throughout the supply chain from production to end-use. Durability, defined as the ability to withstand mechanical handling and transport without significant degradation, is arguably the most critical quality parameter for commercial viability, with acceptable values typically exceeding 90% and premium products achieving 95-98% in standardized tumbling tests [3]. Durable briquettes minimize product loss during handling, reduce dust emissions that create workplace hazards, and maintain consistent feeding characteristics in automated combustion systems. Hardness provides complementary information about resistance to localized deformation and penetration, influencing behavior during storage under load and in combustion appliances [12]. Both properties are rooted in the quality and extent of inter-particle bonding developed during densification, particularly the formation of durable solid bridges from thermally activated lignin. The parameters that promote high density generally promote high durability and hardness, but the relationships are not perfectly linear because mechanical resilience depends specifically on bond strength at particle interfaces rather than simply on the degree of compaction [10]. Ali, et al. [20] emphasized that both properties should be evaluated in comprehensive quality assessment programs, as they provide different insights into briquette behavior under the diverse stress conditions encountered in real-world applications, from stacking in storage silos to feeding in combustion systems. Table 4 summarizes the effects of key parameters on physical and mechanical properties.

Table 4: Influence of Key Parameters on Physical and Mechanical Properties [2-4]

Parameter	Effect on Density	Effect on Durability	Effect on Hardness	Optimal Range
Compaction Pressure	Strong positive up to threshold	Positive; threshold exists	Positive; follows density	100-200 MPa (feedstock dependent)
Temperature	Moderate positive	Strong positive (lignin activation)	Strong positive	100-160°C (lignin Tg range)
Moisture Content	Optimal window (8-15%)	Optimal window (8-15%)	Optimal window (8-15%)	8-12% (woody); 10-15% (agricultural)
Particle Size (fines content)	Positive with optimal gradation	Positive with optimal gradation	Positive with optimal gradation	30-50% fines (<1 mm)
Retention Time	Moderate positive	Positive (stress relaxation)	Positive	1-30 sec (technology dependent)
Lignin Content	Positive (binding capacity)	Strong positive	Strong positive	>20% desirable

4.2. Combustion Properties

The combustion properties of biomass briquettes ultimately determine their value as a fuel and their suitability for various thermal conversion applications. While physical and mechanical properties govern handling and storage, combustion characteristics directly influence performance in end-use devices, from domestic stoves to industrial boilers. These properties are primarily determined by feedstock chemical composition, though densification can indirectly influence combustion behavior through physical structure and thermal history during production. The most critical combustion properties include calorific value, which quantifies energy content, and proximate analysis parameters—volatile matter, fixed carbon, and ash content—which describe fuel behavior during thermal conversion [2, 3].

4.2.1. Calorific value

Calorific value represents the most fundamental measure of fuel quality, quantifying energy released during complete combustion. Higher Heating Value (HHV) includes latent heat of water vaporization, while Lower Heating Value (LHV) excludes it, representing energy available in practical systems where flue gases exit above condensation temperature [7]. For biomass briquettes, HHV typically ranges from 16-20 MJ/kg, with woody materials at the higher end and agricultural residues lower due to higher mineral and lower lignin contents. Calorific value is primarily determined by chemical composition, with lignin possessing the highest energy content (25-26 MJ/kg) compared to cellulose and hemicellulose (17-18 MJ/kg). Extractives such as resins can exceed 30 MJ/kg, enriching feedstocks that contain them [8]. Song, et al. [25] reported that each 1% increase in lignin content raises HHV by approximately 0.1 MJ/kg. The densification process does not significantly alter mass-based calorific value, but dramatically increases volumetric energy density—the product of calorific value and briquette density—which is critical for logistics [15]. Table 5 presents Calorific Values of Selected Biomass Feedstocks and Briquettes.

Table 5: Calorific Values of Selected Biomass Feedstocks and Briquettes

Biomass Type	Higher Heating Value (MJ/kg)	Volumetric Energy Density (GJ/m³)	Reference
Pine Wood	19.5-20.5	20-24	[15]
Wheat Straw	16.5-17.5	15-18	[15]
Rice Husk	15.0-16.0	14-17	[28]
Torrefied Wood	21.0-23.0	22-26	[28]

4.2.2. Proximate Analysis (Volatile Matter, Fixed Carbon and Ash Content)

Proximate analysis partitions biomass into moisture, volatile matter, fixed carbon, and ash, providing essential information for combustion system design. These parameters are primarily inherited from the feedstock, though thermal pre-treatments can modify them [15]. Volatile Matter represents the fraction released as gases when fuel is heated in the absence of air, typically constituting 70-85% of dry biomass. This high volatile content distinguishes biomass from coal and necessitates combustion systems designed for gas-phase combustion with adequate mixing and residence time [28]. Biomass combustion occurs in two stages: devolatilization with gas-phase combustion, followed by char combustion. Thermal pre-treatments such as torrefaction can reduce volatile content by 10-30%, producing fuels with intermediate characteristics [15].

Fixed Carbon represents the solid carbonaceous residue that undergoes heterogeneous combustion at higher temperatures, typically ranging from 12-22% in biomass. Fixed carbon derives primarily from lignin and correlates positively with lignin content. During combustion, fixed carbon burns more slowly than volatiles, requiring longer residence times at high temperature. The volatile-to-fixed carbon ratio is an important design parameter influencing combustion chamber geometry and operating conditions. Higher fixed carbon fuels produce longer-lasting char beds desirable for cooking and residential heating [29].

Ash Content represents the inorganic residue after complete combustion, varying from 0.3% in clean wood to 20-25% in rice husks. High ash content reduces calorific value, increases residue disposal requirements, and can cause slagging, fouling, and corrosion [30]. Alkali metals, particularly potassium, lower ash melting temperatures and promote deposit formation, while silicon reacts with alkalis to form problematic silicates [29]. Agricultural residues typically have higher and more problematic ash compositions than woody biomass. Ash content is primarily determined by feedstock selection, though washing or leaching can reduce it for problematic materials [29]. Table 6 highlights the proximate analysis of selected biomass feedstocks (dry basis)

Table 6: Proximate Analysis of Selected Biomass Feedstocks (Dry Basis)

Biomass Type	Volatile Matter (%)	Fixed Carbon (%)	Ash Content (%)	Reference
Pine Wood	82-86	13-17	0.3-0.6	[13]
Wheat Straw	73-78	16-20	5.0-9.0	[5, 14]
Rice Husk	63-68	15-18	15-22	[15]
Torrefied Wood	60-70	28-38	0.5-1.5	[18]

4.3. Relevance to Thermal Conversion Efficiency

Combustion properties directly determine achievable thermal conversion efficiency—the proportion of fuel energy transferred for useful purposes. High volatile matter requires combustion systems with sufficient volume and mixing for complete gas-phase oxidation; incomplete combustion causes energy losses and emissions [31]. Fixed carbon requires adequate temperature, oxygen, and residence time for complete conversion. The balance between volatile and fixed carbon influences optimal design of staged combustion systems. Ash content and composition affect efficiency through deposit formation and heat transfer. High-ash fuels require more frequent cleaning of heat exchange surfaces, and ash deposits insulate surfaces, reducing efficiency [17]. Alkali metals vaporize and condense on cooler surfaces, forming sticky deposits that accelerate fouling. Potassium is particularly problematic, with Fenta, et al. [12] reporting that potassium contents above 0.2% in fuel significantly increase fouling propensity. Physical briquette properties also influence combustion. Higher density fuels burn more slowly, providing longer heat release periods advantageous for overnight heating [22]. Uniform size and density facilitate predictable combustion and precise air-fuel control. Durable briquettes maintain integrity during heating, providing consistent void spaces for air flow, while friable briquettes produce fines that impede air distribution [22]. Understanding these relationships enables optimization of both densification parameters and feedstock selection to produce fuels tailored to specific applications.

5. CONCLUSION

This review highlights that the quality of biomass briquette depends on an interconnected relationship between lignin chemistry, moisture content, compression pressure and temperature interactions. Thermoplastic behavior of lignin above its glass transition temperature makes it the main natural binder.

Within a small optimal range of 8-15% moisture works both to plasticize and lubricate. The pressure serves to rearrange the particles and eliminate any voids, while the temperature activates lignin flow and solid bridge formation. The final density, durability, and combustion properties are determined by their synergistic interaction and depend on particle size distribution. Key areas of future work include predictive models correlating feedstock characteristics with ideal processing conditions, systematic investigations of nontraditional and mixed feedstocks, and approaches to translating laboratory observations to continuous industrial operations. The resolution of these gaps will drive faster process optimization and minimize empirical trial-and-error. Its optimized densification converts low value residues into standardized renewable fuels, displacing fossil carbon, reducing methane emissions, and creating opportunities for rural economies. Progressing briquetting science toward a predictive understanding is critical to the development of the robust feedstock supply chains necessary for sustainable bioenergy systems in a circular bioeconomy.

REFERENCES

[1] M. Wu, K. Wei, J. Jiang, B. B. Xu, and S. Ge, "Advancing green sustainability: A comprehensive review of biomass briquette integration for coal-based energy frameworks," *International Journal of Coal Science & Technology,* vol. 12, no. 1, pp. 1–26, 2025.

[2] N. Tingzhou, Z. Yue, Q. Xuewu, and Z. Lei, "Design of bidirectional screw extrusion biomass honeycomb briquette machine," *International Journal of Mechatronics & Applied Mechanics,* no. 19, 2025.

[3] I. F. Okpala, I. U. Onyenanu, V. C. Ezechukwu, and C. E. Ilochonwu, "Performance Optimization of a Locally Developed Charcoal Briquette Machine Using Response Surface Methodology," *Scientific Journal of Engineering, and Technology,* vol. 2, no. 1, pp. 55–66, 2025.

[4] R. O. Bolaboro, M. S. Abolarin, H. I. Morkah, A. O. Openibo, O. I. Ogunwede, and K. T. Obanimomo, "Design and Fabrication of a Solar Powered Sawdust Briquette Machine for Okra Preservation," *UNIABUJA Journal of Engineering and Technology (UJET),* vol. 2, no. 2, pp. 287–302, 2025.

[5] S. E. Ibitoye *et al.*, "Design and construction of low-cost biomass pyrolysis reactor for research and teaching in universities and colleges," *Biomass Conversion and Biorefinery,* vol. 15, no. 12, pp. 18887–18903, 2025.

[6] P. Bisht *et al.*, "Microwave-assisted pyrolysis of biomass for bioenergy production," *Renewable and Sustainable Energy Reviews,* vol. 226, p. 116344, 2026.

[7] S. Anis *et al.*, "Design, Fabrication and Performance Test of Arduino-Based Automatic Cutting Tool for Coconut Shell Charcoal Briquettes," *Journal of Advanced Research Design,* vol. 137, no. 1, pp. 17–32, 2025.

[8] S. Namadi, A. Musa, and U. Gana, "Design, construction, and performance evaluation of a low-cost portable moulder for biofuel briquette production," *International Journal of Novel Research in Physics Chemistry & Mathematics,* vol. 11, no. 2, pp. 31–43, 2024.

[9] Z. Lu, Z. Tang, L. Wang, S. Wang, and X. Li, "Design and application of the newly developed industrial biomass briquette hot air furnace system," *Applied Thermal Engineering,* vol. 256, p. 124130, 2024.

[10] O. Kabas, U. Ercan, and M. N. Dinca, "Prediction of briquette deformation energy via ensemble learning algorithms using physico-mechanical parameters," *Applied Sciences,* vol. 14, no. 2, p. 652, 2024.

[11] O. Gwatidzo, G. Tigere, O. A. Zingwaru, and F. Masomera, "Design and Testing of a Low-Cost Manually Operated Briquette Press for Sustainable Biomass Utilisation," *i-Manager's Journal on Mechanical Engineering,* vol. 14, no. 4, 2024.

[12] E. W. Fenta, M. M. Ayele, B. A. Mebratie, and G. T. Tefera, "Adaptive design and development of a screw press water hyacinth briquetting machine and characterization of the water hyacinth briquette's combustion properties," *Biomass Conversion and Biorefinery,* vol. 14, no. 19, pp. 24241–24251, 2024.

[13] A. R. Ige and G. Łaska, "Production of antioxidant additives and biochar pellets from the Co-pyrolysis of agricultural biomass: A review," *Renewable and Sustainable Energy Reviews,* vol. 208, p. 115037, 2025.

[14] J. Hao, F. Xu, D. Yang, B. Wang, Y. Qiao, and Y. Tian, "Analytical pyrolysis of biomass using pyrolysis-gas chromatography/mass spectrometry," *Renewable and Sustainable Energy Reviews,* vol. 208, p. 115090, 2025.

[15] F. H. Hamid, K. S. Yunita, M. Mashuni, M. Jahiding, and E. S. Hasan, "A Review on Carbon Materials Derived from Biomass Pyrolysis for Supercapacitor Applications," *Indonesian Journal of Green Chemistry,* vol. 2, no. 1, pp. 53–70, 2025.

[16] K. J. Abioye, K. J. Falua, M. Rezaee, M. A. Zamiri, F. Zou, and B. Acharya, "Global insights into biomass pyrolysis mechanisms: A scientometric and mechanistic approach," *Results in Engineering,* p. 107123, 2025.

[17] P. Yan *et al.*, "Advances in lignocellulosic biomass pyrolysis and catalytic upgrading for sustainable biofuel production: process design strategies and reaction rationales," *Green Chemistry,* vol. 27, no. 35, pp. 10444–10477, 2025.

[18] S. E. Ibitoye, R. M. Mahamood, T.-C. Jen, C. Loha, and E. T. Akinlabi, "Design and fabrication of biomass densification machine for teaching and research purposes," *Biomass Conversion and Biorefinery,* vol. 14, no. 19, pp. 24253–24264, 2024.

[19] S. G. Azevedo, T. Sequeira, M. Santos, and L. Mendes, "Biomass-related sustainability: A review of the literature and interpretive structural modeling," *Energy,* vol. 171, pp. 1107–1125, 2019.

[20] A. Ali *et al.*, "Insight into the biomass-based briquette generation from agro-residues: challenges, perspectives, and innovations," *BioEnergy Research,* vol. 17, no. 2, pp. 816–856, 2024.

[21] A. T. Hoang *et al.*, "Insight into the recent advances of microwave pretreatment technologies for the conversion of lignocellulosic biomass into sustainable biofuel," *Chemosphere,* vol. 281, p. 130878, 2021.

[22] M. Tomy, A. M. Aravind, and X. T. Suryabai, "Advances of coconut waste as a sustainable energy storage solution—a comprehensive review," *Biomass Conversion and Biorefinery,* vol. 15, no. 10, pp. 14675–14695, 2025.

[23] V. Singh and A. Singh, "Briquetting Technologies for Minerals and Metallurgical Applications: A Review," *Mineral Processing and Extractive Metallurgy Review,* pp. 1–20, 2025.

[24] H. Tambunan and M. Fahmi, "Characteristics of Agricultural and Plantation Wastes as Solid Biomass Energy Feedstock: A Systematic Review," *Jurnal Konversi Energi dan Manufaktur,* vol. 10, no. 2, pp. 150–161–150–161, 2025.

[25] B. Song, M. Cooke-Willis, R. van Leeuwen, M. Fahmy, and P. Hall, "Insights into the swelling behaviours of biomass and biomass/thermoplastic briquettes under water penetration and moisture adsorption," *Biomass and Bioenergy,* vol. 168, p. 106673, 2023.

[26] A. Brunerová *et al.*, "Manual wooden low-pressure briquetting press: An alternative technology of waste biomass utilisation in developing countries of Southeast Asia," *Journal of Cleaner Production,* vol. 436, p. 140624, 2024.

[27] P. Li *et al.*, "Research progress on the preparation of high-value carbon materials by biomass pyrolysis," *Biomass and Bioenergy,* vol. 193, p. 107520, 2025.

[28] W. Chang *et al.*, "Recent progress on the synergistic preparation of liquid fuels by co-pyrolysis of lignocellulosic biomass and plastic wastes," *Journal of the Energy Institute,* p. 102019, 2025.

[29] K. Laouidi, S. Habchi, C. K. Fanezoune, B. Sallek, N. Kussul, and H. El Bari, "Advancements in artificial neural networks and fast pyrolysis of biomass processing: A comprehensive review and a bibliometric analysis," *Journal of Analytical and Applied Pyrolysis,* vol. 189, p. 107098, 2025.

[30] Z. M. Shakor, Y. M. Tayib, A. A. AbdulRazak, Z. Y. Shnain, and E. Al-Shafei, "Thermogravimetric Analysis Integrated with Mathematical Methods and Artificial Neural Networks for Optimal Kinetic Modeling of Biomass Pyrolysis: A Review," *ACS omega,* vol. 10, no. 33, pp. 36750–36770, 2025.

[31] D. Venegas-Vásconez *et al.*, "Microwave Pretreatment for Biomass Pyrolysis: A Systematic Review on Efficiency and Environmental Aspects," *Processes,* vol. 13, no. 10, p. 3194, 2025.