

Review Article

Advances in the Development and Optimization of Modular Multi-Residue Briquetting Machines: A Comprehensive Review

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Abstract: Growing demand for renewable and sustainable energy sources has fueled interest in biomass briquetting as a useful technique for turning agricultural and forestry waste into high-density solid biofuels. Emerging as a viable answer is modular multi-residue briquetting equipment since it can process many different types of biomass, is scalable, is simple to maintain and may adapt to changing output needs. Emphasizing machine design, densification processes, material preparation, operational settings and performance assessment, this review critically reviews recent developments in the creation and optimization of modular multi-residue briquetting equipment. The review combines results on how biomass properties, moisture content, particle size, compaction pressure, binder use, die design and temperature affect briquette quality parameters including density, compressive strength, endurance, calorific value and combustion efficiency. Moreover, recent developments in modular design, automation, intelligent control systems, energy-efficient drive mechanisms, and computational optimization methods are examined to show their effects on enhanced machine performance and operational effectiveness. Also covered are current problems: feedstock volatility, die wear, energy use, process standardization and inadequate integration of digital monitoring technology. Emerging research directions noted in the review are Internet of Things (IoT)-enabled monitoring, digital twin technology, artificial intelligence-driven process optimization and sustainable manufacturing techniques for next-generation briquetting systems. This review offers insightful analysis for scientists, equipment designers, legislators and renewable energy professionals trying to advance biomass densification technologies for sustainable energy generation, trash valorization and circular bio-economy development by combining current knowledge and pointing out technical gaps.

KEYWORDS: Biomass briquetting, Briquetting systems, Machine optimization, Multi-residue biomass.

Introduction

The global demand for affordable, sustainable and renewable energy sources has accelerated significantly in the twenty-first century, driven by concerns over fossil fuel depletion, climate change, and energy poverty, particularly in developing nations (Agar *et al.*, 2018). Biomass briquetting has emerged as one of the most promising densification technologies that converts loose, voluminous agricultural and industrial residues into compact, high-energy-density solid fuel products

known as briquettes (Grover and Mishra, 1996; Yank *et al.*, 2016). These densified fuel blocks offer superior handling, storage and combustion characteristics compared to raw biomass, making them attractive substitutes for wood, charcoal and fossil fuels in both domestic and industrial energy applications (Kaliyan and Morey, 2009).

Despite the well-documented potential of biomass briquetting, a persistent technological gap remains in the design and commercialization of

machines capable of processing diverse feedstock types simultaneously or interchangeably within a single platform (Oladeji, 2015; Onu *et al.*, 2010). Conventional briquetting equipment tends to be feedstock-specific, requiring operators to procure separate machines for rice husks, sawdust, sugarcane bagasse, corn cobs, or other residues, thereby increasing capital investment and limiting operational flexibility (Husain *et al.*, 2002; Mani *et al.*, 2006). The concept of a multi-residue modular briquette machine directly addresses this limitation by integrating interchangeable compression modules, variable-geometry dies and adaptive control systems into a unified mechanical framework (Tumuluru *et al.*, 2011).

This literature review synthesizes the body of knowledge underpinning the development and optimization of such a machine. It examines the properties of common agricultural and forestry residues used as briquetting feedstocks, the fundamental mechanics of biomass densification, existing briquette machine designs and their limitations, modular engineering principles applicable to briquetting systems, binder and additive research, quality standards for briquette products and optimization methodologies employed in prior engineering studies. The review identifies critical research gaps and establishes a theoretical foundation for the proposed multi-residue modular briquette machine development project.

Biomass Residues as Briquetting Feedstocks Global Availability and Energy Potential

Agricultural residues represent the largest and most distributed category of biomass available for energy conversion worldwide. The Food and Agriculture Organization of the United Nations estimates that global crop residue production exceeds 3.8 billion tonnes annually, with sub-Saharan Africa, South and Southeast Asia accounting for the largest proportional shares (FAO, 2019). Renewables 2021 Global Status Report further highlighted that biomass continues to supply approximately 10% of total global primary energy, with solid biomass residues playing the dominant role in developing economies (REN21,

2021). The calorific values of commonly briquetted residues range from 14 MJ/kg for rice husks to over 19 MJ/kg for dry sawdust and wood shavings, positioning them as viable alternatives to low-grade coal (Bhattacharya *et al.*, 2002; Oladeji, 2010).

In Nigeria and across West Africa, residues including groundnut shells, rice husks, sugarcane bagasse, corn cobs and cassava peels are generated in vast quantities yet remain largely underutilized or openly burned, contributing to greenhouse gas emissions and environmental degradation (Jekayinfa and Scholz, 2009). (Abdullahi *et al.*, 2020) estimated that Nigeria alone generates over 227 million tonnes of agricultural waste annually, with the energy recovery potential exceeding 1.4 EJ if appropriate densification technologies were deployed. The development of a multi-residue briquette machine capable of exploiting this heterogeneous waste stream is therefore not only technically relevant but also of significant socioeconomic importance.

Physio-Chemical Properties of Key Residues Rice Husk

Rice husk is one of the most extensively studied briquetting feedstocks due to its global abundance, with annual production exceeding 120 million tonnes worldwide (Giddel and Jivan, 2007). It is characterized by a high silica content (15–20% as SiO₂), low bulk density (80–120 kg/m³), high ash content (18–22%) and relatively low calorific value compared to other lignocellulosic materials (Suramaythangkoor and Gheewala, 2008). The high silica content of rice husk poses specific challenges for briquetting, as it accelerates die wear and requires higher compaction pressures to achieve acceptable briquette density (Yank *et al.*, 2016). (Gómez *et al.*, 2014) demonstrated that rice husk briquettes produced at pressures above 150 MPa and temperatures between 100°C and 120°C exhibited satisfactory mechanical durability, though combustion residue management remained problematic due to the high ash fraction.

Sawdust and Wood Shavings

Sawdust and wood shavings originating from timber processing industries exhibit favourable

briquetting characteristics including high lignin content (25–35%), low ash content (less than 2%) and calorific values between 17 and 20 MJ/kg (Giddel and Jivan, 2007; Kaliyan and Morey, 2009). The lignin present in woody residues acts as a natural thermoplastic binder when heated above its glass transition temperature (approximately 70–80 °C), enabling binder-free briquette production under moderate temperatures and pressures (Tumuluru *et al.*, 2011). (ObidziDski, 2012) reported that sawdust briquettes produced at 100 °C achieved compressive strength values exceeding 5 MPa and water resistance suitable for outdoor storage, making them among the highest-quality biomass briquettes commercially available.

Sugarcane Bagasse

Sugarcane bagasse is the fibrous residue remaining after juice extraction from sugarcane stalks, with an estimated global production exceeding 540 million tonnes per year (Velázquez-Martí *et al.*, 2011). It contains approximately 45–55% cellulose, 20–25% hemicellulose, 18–24% lignin, and 1–4% ash, making it well-suited for briquetting when properly pre-treated (Parikh *et al.*, 2005). The high initial moisture content of freshly harvested bagasse (45–55% wet basis) necessitates significant drying prior to briquetting, adding operational complexity and energy cost (Husain *et al.*, 2002). Briquettes produced from sugarcane bagasse exhibit moderate calorific values of 15–17 MJ/kg and acceptable mechanical strength when binders are employed, though their hygroscopic nature requires moisture-proof packaging for extended storage (Grover and Mishra, 1996).

Corn Cobs and Stalks

Corn cobs possess a distinctive cellular structure that imparts relatively low density (100–150 kg/m³) but high porosity, which facilitates rapid moisture removal during briquetting (Kaliyan and Morey, 2010). The calorific value of corn cob briquettes ranges from 16 to 18 MJ/kg, comparable to low-rank coal, and their low sulphur content makes combustion environmentally cleaner than fossil alternatives (Mani *et al.*, 2006). (Adegoke

et al., 2019) found that optimized corn cob briquettes with cassava starch binder (5% w/w) achieved a relaxed density of 820 kg/m³ and a compressive strength of 3.8 MPa, satisfying criteria for household and small industrial use in Nigeria.

Biomass Densification: Fundamental Mechanics Compaction Theory

Biomass densification is governed by three primary inter-particle bonding mechanisms: solid bridges formed by binders or softened lignin, van der Waals attraction forces between particles at very close proximity and mechanical interlocking of irregularly shaped particles under compression (Tumuluru *et al.*, 2011). During compaction, biomass particles undergo three sequential stages: rearrangement and packing, elastic and plastic deformation and fragmentation or particle bonding at high pressures as cited in (Kaliyan and Morey, 2009). The transition between these stages depends on the viscoelastic properties of the feedstock, which are strongly influenced by moisture content, particle size, temperature and applied pressure.

(Kawakita and Lüdde, 1971) proposed a widely applied empirical model to describe the compressibility of powder and biomass materials, relating applied pressure to volumetric reduction through two material constants representing initial porosity and yield strength. This model has been successfully adapted for briquetting research by (Mani *et al.*, 2004), who demonstrated that the compressibility constants for straw, corn stover and switchgrass differed significantly, highlighting the need for feedstock-specific process optimization. More recently, (Larsson *et al.*, 2015) employed finite element analysis (FEA) to simulate stress distribution within biomass briquettes during piston-cylinder compression, identifying stress concentration zones near die walls as a primary cause of surface cracking and reduced briquette durability.

Effect of Process Variables

Moisture Content

Moisture content is among the most critical process variables influencing briquette quality, acting as a plasticizer that softens cell walls and facilitates inter-

Table 1. Biomass feedstock properties and briquetting use.

Biomass Residue	Key Physico-Chemical Properties	Calorific Value	Briquetting Behaviour / Processing Notes	Reference(s)
Rice Husk	Bulk density: 80-120 kg/m ³ Silica content: 15-20% (as SiO ₂) Ash content: 18-22% Annual global production: >120 million tonnes	Relatively low (vs. other lignocellulosic residues)	High silica accelerates die wear; requires higher compaction pressure for acceptable density. Satisfactory mechanical durability achieved at pressures >150 MPa and die temperatures 100-120 °C; combustion residue (ash) management remains problematic. Optimal moisture range narrower (5-10%) than other feedstocks owing to high silica content.	(Yank <i>et al.</i> , 2016) (Giddel and Jivan, 2007) (Suramaythangkoor and Gheewala, 2008) (Gómez <i>et al.</i> , 2014)
Sawdust & Wood Shavings	Lignin content: 25-35% Ash content: <2% Lignin softens (natural thermoplastic binder) above ~70-80 °C	17-20 MJ/kg	High lignin enables binder-free briquetting under moderate heat/pressure. Briquettes produced at 100 °C achieved compressive strength >5 MPa and water resistance suitable for outdoor storage - among the highest-quality biomass briquettes commercially available.	(Kaliyan and Morey, 2009) (Tumuluru <i>et al.</i> , 2011) (Giddel and Jivan, 2007) (Obidziński, 2012)
Sugarcane Bagasse	Cellulose: 45-55%; Hemicellulose: 20-25%; Lignin: 18-24%; Ash: 1-4% Fresh moisture content: 45-55% (wet basis) Global production: >540 million tonnes/year	15-17 MJ/kg	High initial moisture requires significant pre-drying, adding operational cost and complexity. Acceptable mechanical strength achieved when binders are used; hygroscopic nature requires moisture-proof packaging for storage.	(Grover and Mishra, 1996) (Husain <i>et al.</i> , 2002) (Velázquez-Martí <i>et al.</i> , 2011) (Parikh <i>et al.</i> , 2005)
Corn Cobs & Stalks	Bulk density: 100-150 kg/m ³ (low density, high porosity) Low sulphur content	16-18 MJ/kg (comparable to low-rank coal)	High porosity facilitates rapid moisture removal during briquetting. With 5% w/w cassava starch binder, optimized briquettes achieved relaxed density of 820 kg/m ³ and compressive strength of 3.8 MPa - meeting household/small-industrial use criteria in Nigeria.	(Mani <i>et al.</i> , 2006) (Kaliyan and Morey, 2010) (Adegoke <i>et al.</i> , 2019)

particle bonding at moderate levels, yet reducing strength and promoting fungal degradation at excessive levels (Kaliyan and Morey, 2009). The optimal moisture content for most lignocellulosic feedstocks during briquetting lies between 8% and 15% wet basis, though this range shifts toward 5–10% for high-silica materials like rice husk (Yank *et al.*, 2016); (Bhattacharya *et al.*, 2002). (Mani *et al.*, 2006) reported a negative correlation between moisture content above 12% and compressive strength in barley straw briquettes, attributing this

to steam generation within the die that disrupts particle bonding during rapid decompression.

Particle Size

Particle size and size distribution exert dual influence on briquette quality: finer particles increase surface area available for bonding and promote denser packing, while very fine particles (<0.5 mm) can impair binding by disrupting the fibrous interlocking that contributes to mechanical strength in lignocellulosic materials (Demirbas,

2004). (Mani *et al.*, 2004) found that reducing corn stover particle size from 3.2 mm to 0.8 mm increased briquette density by approximately 17% but did not proportionally improve compressive strength, suggesting an optimal size range. For multi-residue applications, where feedstocks with inherently different morphologies are processed, the ability to adjust grinding parameters within the machine system becomes essential for consistent output quality (ObidziDski, 2012).

Temperature and Pressure

Elevated temperature during briquetting softens lignin and activates thermoplastic bonding between particles, significantly reducing the pressure required to achieve a given briquette density (Kaliyan and Morey, 2009). The relationship between applied pressure, temperature and resulting briquette density follows a non-linear response surface that has been characterized using response surface methodology (RSM) for various feedstocks (Adapa *et al.*, 2010). (Mangena and du Cann, 2007) demonstrated through central composite design experiments that optimal briquetting conditions for coal fines (analogous to fine biomass) occurred at

either mechanical (flywheel-driven) or hydraulic principles, represent the oldest and most widely deployed commercial briquetting technology (Grover and Mishra, 1996). Mechanical piston presses achieve high production throughput (200–1000 kg/h) through rapid reciprocating motion at frequencies of 200–500 strokes per minute, making them economically viable for large-scale operations (Husain *et al.*, 2002). However, their high noise levels (>90 dB), complex maintenance requirements, and susceptibility to impact wear on dies and pistons make them less suitable for small and medium enterprise (SME) settings in developing countries (Oladeji, 2015). Hydraulic piston presses operate at lower frequencies but higher pressures (up to 400 MPa), producing denser and more uniform briquettes suitable for industrial fuel applications, yet their slower cycle times limit production capacity (Mani *et al.*, 2006). Figure 1 illustrates the piston press operating sequence described in this section.

Screw Press (Extruder) Machines

Screw extrusion briquetting machines use a helical screw rotating within a tapered barrel to continuously

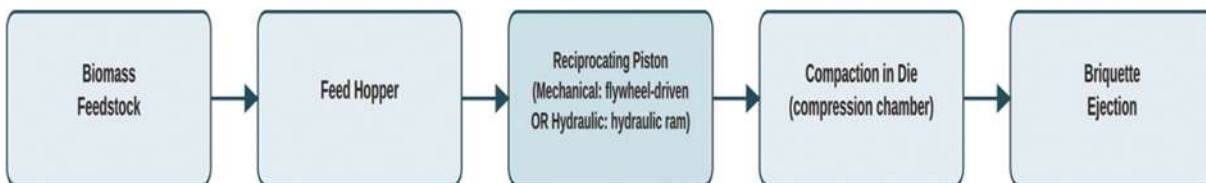


Fig. 1. Operating principle of piston press briquetting machines, showing the mechanical (flywheel-driven) and hydraulic (hydraulic ram) variants discussed in section 4.1.

the intersection of high pressure (200–250 MPa) and moderate temperature (80–120 °C), beyond which marginal density gains failed to justify increased energy consumption. These findings underscore the importance of incorporating temperature control systems into briquette machine designs targeting multiple feedstock types.

Existing Briquette Machine Designs and Their Limitations

Piston Press Machines

Piston press briquetting machines, operating on

compress and extrude biomass through a heated conical die, producing cylindrical or hollow briquettes with distinctive surface glazing that improves moisture resistance (Tumuluru *et al.*, 2011); (Bhattacharya *et al.*, 2002). The continuous extrusion process allows for high throughput and consistent product geometry, while die heating (typically 250–350°C) activates lignin softening even for low-lignin feedstocks. However, screw extruders suffer from rapid wear of the screw flights and barrel liners when processing abrasive materials such as rice husk, necessitating costly component

replacement at intervals as short as 100–200 operating hours (Giddel and Jivan, 2007). The thermal energy requirement for screw extrusion also represents 20–40% of total machine energy consumption, reducing the net energy ratio of briquette production (Parikh *et al.*, 2005). Figure 2 illustrates the screw press (extruder) machines operating sequence described in this section.

Roller Press (Pellet Mill) Machines

Roller press briquetting machines, including flat die and ring die pellet mills, compress biomass between counter-rotating rolls or between rolls and a

Vibration-Assisted and Emerging Technologies

Recent advances in briquetting technology have introduced vibration-assisted compaction, ultrasonic densification, and microwave pre-treatment as methods to reduce compaction pressures and improve briquette quality for challenging feedstocks (Tumuluru *et al.*, 2011); (Deng *et al.*, 2017). (Deng *et al.*, 2017) reported that ultrasonic vibration at 40 kHz applied during biomass compaction reduced required pressure by 30–45% while increasing briquette density by 8–12% compared to static compaction, suggesting promising implications for energy-efficient multi-feedstock processing.

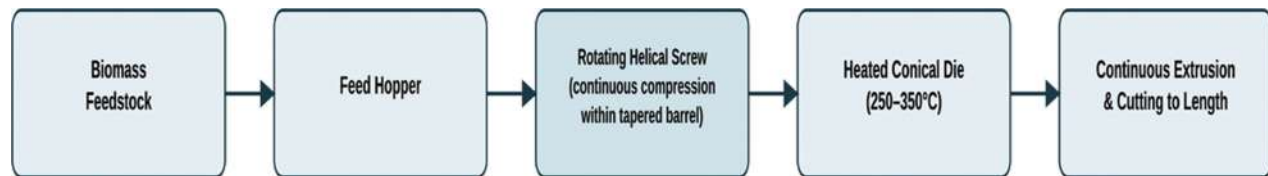


Fig. 2. Operating principle of screw press (extruder) briquetting machines, corresponding to the process described in section 4.2.

perforated die plate to produce pellets or pillow-shaped briquettes (Kaliyan and Morey, 2010). While pellet mills are optimized for producing uniform 6–12 mm diameter pellets at high throughput, they require feedstock with very narrow moisture (8–12%) and particle size (<3 mm) specifications, limiting their adaptability to heterogeneous agricultural residues (Larsson *et al.*, 2015). Roll press machines producing larger briquettes (25–100 mm) offer better feedstock flexibility but struggle with fine or fibrous materials that do not flow uniformly through the roll gap (Obidziński, 2012). Neither technology incorporates modularity features that would allow rapid adaptation to new feedstock types without major mechanical reconfiguration. Figure 3 illustrates the roller press (pellet mill) machines operating sequence described in this section.

Microwave pre-treatment of biomass prior to briquetting has been shown to selectively heat and partially depolymerize lignin, enhancing inter-particle bonding at lower compaction pressures (Azargohar *et al.*, 2014). These emerging technologies, while not yet commercially mainstream, offer conceptual modules that could be integrated into an advanced modular briquette machine platform.

Modular Engineering Principles in Machine Design

Concept and Classification of Modularity

Modularity in mechanical engineering refers to the design philosophy of constructing a system from distinct, interchangeable and independently functioning subsystems (modules) that can be combined, rearranged, or replaced without

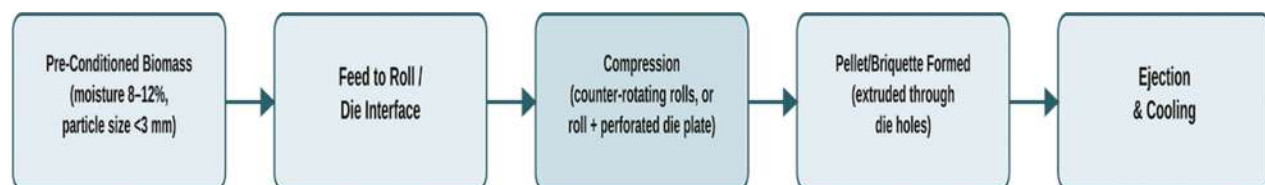


Fig. 3. Operating principle of roller press (pellet mill) briquetting machines, corresponding to the process described in section 4.3.

Table 2. Briquetting machine types: principles, feedstock suitability and limitations.

Machine Type	Working Principle	Suitable Feedstock	Typical Capacity	Key Limitations	Reference(s)
Mechanical Piston Press (Flywheel-Driven)	Reciprocating piston driven by a flywheel mechanically compresses biomass into a die at high stroke frequency.	General-purpose; widely used across sawdust, corn cob, and bagasse feedstocks.	200-1,000 kg/h; 200-500 strokes/min	High noise levels (>90 dB) Complex maintenance Susceptible to impact wear on dies/pistons Less suitable for SME settings in developing countries	(Oladeji, 2015) (Husain et al., 2002)
Hydraulic Piston Press	Hydraulically actuated piston applies sustained high pressure at lower stroke frequency than mechanical presses.	Feedstocks requiring dense, uniform briquettes for industrial fuel use.	Up to 400 MPa pressure; slower cycle times	Slower cycle times limit production capacity Higher capital cost for hydraulic systems	(Mani et al., 2006)
Screw Press (Extruder)	Helical screw rotates within a tapered barrel, continuously compressing and extruding biomass through a heated conical die (typically 250-350°C).	Low-lignin feedstocks (die heating activates lignin softening); produces cylindrical/hollow briquettes with glazed, moisture-resistant surface.	High, continuous throughput	Rapid wear of screw flights and barrel liners with abrasive materials (e.g., rice husk) Component replacement as often as every 100-200 operating hours Thermal energy demand = 20-40% of total machine energy consumption	(Tumuluru et al., 2011) (Bhattacharya et al., 2002) (Giddel and Jivan, 2007) (Parikh et al., 2005)
Roller Press (Flat/Ring Die Pellet Mill)	Biomass compressed between counter-rotating rolls or between rolls and a perforated die plate.	Feedstock with narrow moisture (8-12%) and fine particle size (<3 mm); larger roll-press variants tolerate coarser material.	6-12 mm pellets (die); 25-100 mm briquettes (roll press)	Very narrow moisture/particle-size tolerance limits adaptability to heterogeneous residues Fine or fibrous materials flow poorly through the roll gap No inherent modularity for rapid feedstock changeover	(Obidziński, 2012) (Kaliyan and Morey, 2010) (Larsson et al., 2015)
Vibration-Assisted / Emerging Technologies	Ultrasonic vibration (e.g., 40 kHz) or microwave pre-treatment applied during or before compaction to soften lignin and reduce required pressure.	Challenging feedstocks where conventional compaction pressure/energy demand is high.	Not yet commercial-scale; pilot/research stage	Not yet commercially mainstream Additional equipment (ultrasonic/microwave units) adds cost and complexity	(Deng et al., 2017) (Azargohar et al., 2014)

redesigning the entire system (Ulrich, 1995). (Pahl and Beitz, 1996) classified machine modularity into three categories: functional modularity (where each module performs a distinct function), parametric modularity (where modules vary in size or capacity

but share common interfaces) and technology modularity (where alternative technological approaches are encapsulated in interchangeable modules). For a multi-residue briquette machine, all three modular classes are relevant: functional

modules for feeding, grinding, mixing, compressing, and cutting; parametric modules for varying die sizes and compression ratios; and technology modules for selecting between screws, hydraulic, or mechanical compression mechanisms.

The advantages of modular machine design extend beyond operational flexibility to include reduced spare parts inventory, simplified maintenance, scalability of production capacity, and facilitation of incremental product improvement without complete redesign (Simpson *et al.*, 2006). (Seliger *et al.*, 2008) demonstrated through industrial case studies that modular machine platforms reduced time-to-market for new product variants by 35–60% compared to dedicated single-purpose machines, while also reducing total lifecycle costs by 20–30%. These documented advantages strongly support the modular design paradigm for a briquette machine intended to serve diverse feedstock environments across Sub-Saharan Africa and similar regions.

Interface Standardization and Coupling Design

The functionality of a modular machine system critically depends on the design of standardized mechanical, electrical and control interfaces that allow modules to be coupled and decoupled reliably (Pahl and Beitz, 1996). In agricultural machinery, quick-coupling mechanisms based on ISO standards for power take-off (PTO) shafts and three-point

hitches have demonstrated the viability of rapid module interchange under field conditions (ASABE, 2012). For briquette machine applications, (Onu *et al.*, 2010) proposed a flanged cylindrical interface standard for die and compression chamber interchange, enabling die replacement in under five minutes using standard tools. (Zhu *et al.*, 2020) extended this concept by developing a universal mounting frame with electrically actuated locking pins that could interface with dies of different geometries while maintaining alignment tolerances of ± 0.05 mm, critical for preventing die jamming during high-pressure compression.

Modular Architecture: Adapting One Machine for Multiple Biomass Types

The core limitation of traditional briquetting equipment is rigid engineering. A machine designed for sawdust fails when fed agricultural straws because different residues possess entirely different densities, elastic recoveries, and chemical compositions. To transform a single machine into a multi-residue modular briquetting system, specific high-wear and process-defining components must be engineered as interchangeable, adjustable modules. The decision logic for selecting interchangeable modular components based on the properties of the biomass feedstock being processed, is shown in figure 4.

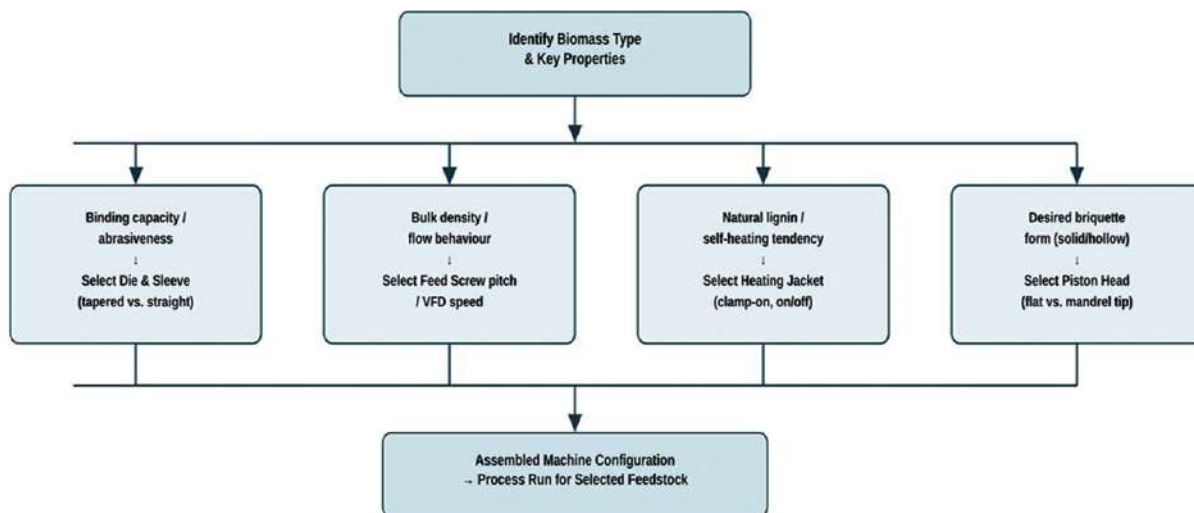


Fig. 4. Decision logic for selecting interchangeable modular components (die/sleeve, feed screw, heating jacket, piston head) based on the properties of the biomass feedstock being processed, corresponding to section 5.2.1.

Key Modular Components of the Machine:

A. The Die and Sleeve Assembly (The Compaction Chamber): This is the most crucial modular zone. Biomass types with low natural binding agents (like rice husk) require a tapered die to build higher backpressure. Highly fibrous biomass (like coconut coir) requires a long, straight die to prevent immediate structural expansion (spring back). By using a modular housing where the internal die sleeve can be slipped out and swapped (e.g., changing from a 5° tapered sleeve to a 2° tapered sleeve), the same machine can process highly divergent materials.

B. Variable Pitch Feeding Screws/Augers: Low-bulk-density materials (straws, grasses) require a large volumetric displacement to feed them into the compaction zone. Heavy, high-density materials (palm kernel shells) require less volume but more torque. A modular drive shaft allowing operators to swap the compression screw or adjust its speed via a Variable Frequency Drive (VFD) is essential.

C. Interchangeable Heating Jackets: Some materials require intensive external heat to melt their natural lignin, while others generate enough frictional heat on their own. The heating element must be a clamp-on, modular induction or resistance jacket that can be plugged into the control system or removed based on the recipe.

D. Adjustable Piston Heads/Tips: The face of the ram or piston can be modularly changed. For example, a flat-faced piston yields solid briquettes, while a piston tip with a central mandrel creates hollow, log-type briquettes which burn faster due to increased surface area.

Computer-Aided Design in Modular Agricultural Machinery

The development of modular agricultural machinery has been significantly accelerated by computer-aided design (CAD) and computer-aided engineering (CAE) tools that enable virtual prototyping and analysis of complex multi-module assemblies (Deng *et al.*, 2017). Finite element

analysis (FEA) has been extensively applied to optimize the structural design of briquette machine frames, die assemblies, and compression chambers, identifying stress concentration zones and enabling targeted material selection and geometry refinement before physical prototyping (Larsson *et al.*, 2015); (Zhu *et al.*, 2020). (Adapa *et al.*, 2010) employed SolidWorks Simulation to analyze von Mises stress distribution in a piston-cylinder briquetting die assembly, demonstrating that chamfered die entry profiles reduced peak stress by 22% compared to sharp-edged dies without compromising compression efficiency. Such virtual design tools are indispensable for the iterative module development process envisaged in a multi-residue modular briquette machine project.

Binders and Additives in Briquette Production Role of Binders

Binders serve to compensate for inadequate natural binding capacity in feedstocks with low lignin content, high silica content, or inherently poor inter-particle cohesion, enabling the production of mechanically durable briquettes at lower pressures and temperatures (Grover and Mishra, 1996). The selection of an appropriate binder must balance technical performance (binding efficiency, thermal stability, water resistance) against economic considerations (cost, local availability) and environmental acceptability (non-toxicity, biodegradability) (Mwampamba *et al.*, 2013).

Organic and Starch-Based Binders

Cassava starch is among the most widely investigated binders for briquette production in Africa and Asia, owing to its low cost, wide availability and effective binding properties at concentrations of 3–8% by weight (Adegoke *et al.*, 2019); (Onukak *et al.*, 2017). (Onukak *et al.*, 2017) compared cassava starch, corn starch and wheat flour as binders for rice husk briquettes in Nigeria, finding that cassava starch at 6% concentration produced briquettes with the highest relaxed density (780 kg/m³) and compressive strength (3.2 MPa), while wheat flour yielded superior water resistance. Molasses, a by-product of sugar refining,

has also been widely used as a binder and energy additive for biomass briquettes, contributing calorific value while improving green strength (Raju *et al.*, 2013). However, high molasses concentrations (>15%) tend to produce sticky briquettes that adhere to die surfaces, increasing wear and reducing production efficiency.

Blending and Co-Briquetting Strategies

Mixing different residues known as co-briquetting is an excellent strategy to engineer a superior hybrid fuel. It allows you to balance out the weaknesses of one material with the strengths of another.

Mixable Categories and Proportions

1.) Category A: The “High-Lignin Binder” + “Low-Lignin Filler”

The Mix: Sawdust (High Lignin) + Rice Husk (Low Lignin, High Ash).

Proportions: 60% Sawdust to 40% Rice Husk.

The Science: Rice husk burns slowly but produces weak briquettes and leaves behind excessive ash. Sawdust acts as a natural binding agent and boosts the calorific value. Blending them allows the sawdust’s melting lignin to trap the loose rice husk particles perfectly.

Best Binder: None needed if processed in a heated modular die (>150 p C); otherwise, use 3% cassava starch.

2.) Category B: The “High-Energy Carbon” + “Fibrous Matrix”

The Mix: Carbonized Coconut Shell (High Energy, Poor Structural Bonding) + Corn Cobs or Sugarcane Bagasse (Fibrous, Lower Energy).

Proportions: 70% Coconut Shell Charcoal to 30% Shredded Corn Cobs/Bagasse.

The Science: Coconut charcoal burns incredibly hot but crumbles into powder easily. Shredded corn cobs provide long, interlocking cellulose fibers that act like a structural rebar mesh inside concrete, holding the dense energy particles together.

Best Binder: 5–8% Molasses or 5% Corn Starch.

3.) Category C: The “Fast-Burning Burner” + “Slow-Burning Anchor”

The Mix: Groundnut (Peanut) Shells (High Volatiles, Ignites Fast) + Coffee Husks (Dense, Burns Slow).

Proportions: 50% Groundnut Shells to 50% Coffee Husks.

The Science: This creates an ideal commercial cooking fuel. The groundnut shells allow the briquette to light up easily without heavy kindling, while the coffee husks maintain a steady, glowing ember bed for hours.

Best Binder: 4% Cassava Starch.

Carbonaceous and Synthetic Binders

For briquettes intended for industrial applications requiring high mechanical strength, carbonaceous binders such as tar pitch, coal tar and petroleum bitumen have been employed to produce hard, dense products with compressive strengths exceeding 10 MPa (Mangena and du Cann, 2007). However, these petroleum-derived binders introduce environmental and health concerns related to polycyclic aromatic hydrocarbon (PAH) emissions during combustion, limiting their acceptability in domestic cooking applications (Mwampamba *et al.*, 2013). Lignosulfonates, obtained as a by-product of the paper pulping industry, represent a promising alternative that combines the binding efficiency of carbonaceous materials with significantly lower toxicity and good biodegradability (Raju *et al.*, 2013). Lignosulfonate-bound briquettes have been shown to achieve compressive strengths of 6–8 MPa with improved moisture resistance compared to starch-bound equivalents.

Briquette Quality Parameters and Standards

Physical Quality Indicators

Physical quality parameters for biomass briquettes include relaxed density, compressive strength, impact resistance, dimensional stability, and surface hardness. Relaxed density, measured 48–72 hours after production to allow stress relaxation, typically ranges from 600 to 1200 kg/m³ for commercially acceptable briquettes, compared to raw biomass bulk densities of 50–200 kg/m³ (Tumuluru *et al.*, 2011). The European pellet standard EN 14961-2 specifies minimum bulk density requirements of

600 kg/m³ and mechanical durability above 97.5% for residential pellets, providing a reference benchmark applicable to larger format briquettes (CEN, 2011). Compressive strength, measured by compression testing machines, should exceed 1 MPa for domestic use briquettes and 3 MPa for industrial fuel applications, according to guidelines established by the Biomass Energy Foundation (Grover and Mishra, 1996).

Combustion and Proximate Analysis

Proximate analysis of briquettes encompasses determination of moisture content, volatile matter, fixed carbon, and ash content, all of which directly influence combustion behaviour and calorific value (Parikh *et al.*, 2005). Briquettes with volatile matter above 70% tend to burn with long, luminous flames suited to domestic cooking but may produce excessive smoke, while those with fixed carbon above 30% produce shorter, hotter flames with lower smoke emissions preferred for gasification and industrial applications (Bhattacharya *et al.*, 2002). (Oladeji, 2010) characterized briquettes from six Nigerian agricultural residues and found that fixed carbon ranged from 11.2% (sugarcane bagasse) to 26.8% (groundnut shells), highlighting the importance of feedstock selection for targeted end-use applications. Ultimate analysis for elemental composition (C, H, N, O, S) further determines emission profiles and fuel classification (Parikh *et al.*, 2005).

Thermal Energy Content and Efficiency

Gross calorific value (GCV), also known as higher heating value (HHV), is the primary thermodynamic parameter distinguishing briquette fuel quality, typically measured using bomb calorimetry according to ASTM D5865 or ISO 1716 standards (ASTM International, 2013). Empirical correlations between proximate analysis results and GCV have been developed by (Parikh *et al.*, 2005) and validated across diverse biomass feedstocks, enabling rapid estimation of calorific value without elaborate calorimetry. For briquettes to be economically competitive with charcoal and firewood in sub-Saharan African markets, GCV should exceed 15 MJ/

kg and moisture content should remain below 12% during the product shelf life, requirements that impose specific constraints on feedstock preparation and post-production packaging (Mwampamba *et al.*, 2013; Jekayinfa and Scholz, 2009).

Optimization Methodologies for Briquette Machine Development

Response Surface Methodology

Response surface methodology (RSM), particularly central composite design (CCD) and Box-Behnken design (BBD), has been extensively employed in briquette production research to characterize the relationships between independent process variables (moisture content, particle size, compaction pressure, temperature, binder concentration) and response variables (density, strength, calorific value, energy consumption) (Adapa *et al.*, 2010); (Kaliyan and Morey, 2009). RSM enables efficient exploration of multi-dimensional process spaces with a relatively small number of experimental runs while simultaneously fitting polynomial regression models that capture both linear and quadratic effects as well as two-factor interactions (Montgomery, 2017). (Yank *et al.*, 2016) applied BBD with three factors at three levels to optimize rice husk briquetting parameters, identifying a saddle-point optimum at 120 MPa pressure, 10% moisture, and 100 °C die temperature that maximized the desirability composite function for density and strength simultaneously.

Taguchi Method and Grey Relational Analysis

The Taguchi method employs orthogonal arrays to systematically study the effects of multiple process parameters on product quality with minimal experimental effort, using signal-to-noise (S/N) ratio analysis to identify robust operating conditions that minimize variability alongside achieving target quality levels (Taguchi *et al.*, 2004, as cited in (Adegoke *et al.*, 2019)). Grey relational analysis (GRA) extends the Taguchi approach to multi-response optimization by converting multiple quality characteristics into a single grey relational grade, enabling simultaneous optimization of competing objectives such as maximizing density

while minimizing energy consumption (Adegoke *et al.*, 2019). (Obidziński, 2012) demonstrated the application of Taguchi L9 orthogonal arrays to the optimization of straw briquette production, identifying screw press speed as the most influential factor for energy efficiency, accounting for 41% of total variance.

Artificial Intelligence and Machine Learning Approaches

Artificial neural network (ANN) models have been increasingly applied to predict briquette quality parameters from process conditions, offering advantages over polynomial RSM models in capturing complex non-linear relationships and extrapolating beyond the experimental design space (Tumuluru *et al.*, 2011); (Azargohar *et al.*, 2014). (Azargohar *et al.*, 2014) trained a feedforward ANN with backpropagation learning using 144 experimental data points for pellet production and achieved prediction accuracies ($R^2 > 0.98$) superior to cubic polynomial RSM models for bulk density and mechanical durability. Genetic algorithm (GA) optimization has been coupled with ANN models to identify globally optimal process parameter combinations, overcoming the local optima limitations of gradient-based methods (Deng *et al.*, 2017). For a multi-residue briquette machine, ANN-based adaptive control systems could theoretically learn feedstock-specific optimal parameters and automatically reconfigure compression and temperature set points when the active module is changed.

Life Cycle Assessment and Techno-Economic Analysis

Life cycle assessment (LCA) has been employed to evaluate the environmental sustainability of briquette production systems from raw material procurement through combustion and ash disposal, identifying hotspots that dominate energy consumption and greenhouse gas emissions (Muazu and Stegemann, 2015). (Muazu and Stegemann, 2015) conducted an attributional LCA of maize cob briquette production in Nigeria and found that the drying stage accounted for 58% of total energy

input and 62% of CO₂-equivalent emissions, suggesting that solar drying integration should be prioritized for environmental optimization. Techno-economic analysis (TEA) frameworks have been applied to quantify the financial viability of briquette enterprises at various production scales, consistently finding breakeven points between 200 and 800 kg/day for single-feedstock machines in African markets (Abdullahi *et al.*, 2020); (Jekayinfa and Scholz, 2009). A modular machine capable of processing multiple residue types would improve feedstock supply security and potentially lower breakeven thresholds by enabling year-round operation independent of a single crop season.

Instrumentation and Control Systems for Briquette Machines

Modern briquette machines increasingly incorporate programmable logic controller (PLC)-based automation systems that monitor and regulate compaction force, die temperature, feed rate, and screw speed in real time, reducing operator dependence and improving product consistency (Zhu *et al.*, 2020). Pressure transducers, thermocouple arrays, load cells, and motor current sensors provide the feedback signals necessary for closed-loop control of key process variables (Larsson *et al.*, 2015). (Seliger *et al.*, 2008) described the implementation of a human-machine interface (HMI) on a reconfigurable manufacturing platform that allowed operators to select pre-programmed module-specific process recipes through a touchscreen interface, reducing setup time for product changeovers from 45 minutes to under 8 minutes. This concept is directly applicable to a multi-residue modular briquette machine, where module-specific PLC recipes could encode optimal compaction parameters for each registered feedstock type, automatically loading the appropriate settings when the active compression module is identified by an RFID or barcode sensor.

Variable frequency drives (VFDs) for motor speed control and proportional-integral-derivative (PID) controllers for temperature regulation represent the minimum instrumentation required for a semi-automated multi-residue briquette machine (Onu

et al., 2010). Power monitoring systems that log energy consumption per production batch provide data essential for validating energy efficiency optimization claims and supporting LCA calculations (Muazu and Stegemann, 2015). Future developments toward fully autonomous adaptive control, guided by machine learning algorithms trained on production data, represent the frontier of smart briquetting technology, though significant sensor integration and data infrastructure challenges must first be addressed in the context of rural developing-country deployment environments (Deng et al., 2017).

Conclusion

This literature review has established a comprehensive theoretical and empirical foundation for the development and optimization of a multi-residue modular briquette machine. The review demonstrates that the global biomass residue resource base is vast and underutilized, that individual feedstocks exhibit distinct physico-chemical characteristics requiring tailored processing conditions, that existing briquette machine technologies are constrained by single-feedstock design philosophies, that modular engineering principles offer a proven pathway to multi-feedstock flexibility and that sophisticated optimization tools including RSM, Taguchi methods, and ANN-GA hybrids are available for systematic machine parameter optimization. The study builds upon this body of knowledge to design a machine that does not merely replicate existing technology but advances it through modularity, multi-objective optimization and adaptive process control, thereby contributing to the technological infrastructure needed to unlock the immense bioenergy potential of agricultural residues in Nigeria and comparable developing economies.

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