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Sustainable Energy from Waste: Experimental Investigation and Optimization of Hybrid Biomass Briquette Production Using a Modified Briquetting Machine

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Abstract

This study investigates the quality performance of hybrid biomass briquettes produced from water hyacinth, sawdust, and rice husk at varying blend ratios using a modified briquetting machine. Fourteen experimental runs were conducted to evaluate the effects of compositional variations on density, shatter index, combustion efficiency, average briquette quality, and desirability. The mixture proportions of water hyacinth (A), sawdust (B), and rice husk (C) ranged between 0.3–0.5kg, 0.2–0.4kg, and 0.1–0.3kg, respectively, ensuring a total blend of 1kg, an equivalence of 100%. The briquette density varied between 0.82 and 0.93 g/cm^3, with the highest value (0.93 g/cm^3) obtained at the optimal blend ratio 0.5:0.4:0.1 (Run 11), which also demonstrated the best overall performance. The shatter index ranged from 83.1% to 90.2%, while combustion efficiency varied from 75.3% to 85.4%, indicating that higher proportions of water hyacinth and sawdust enhanced both mechanical strength and combustion behavior. The average briquette quality ranged from 36.87% to 43.00%, with the maximum (43.00%) recorded at Run 11, corresponding to the optimal blend ratio of 0.5:0.4:0.1. Similarly, desirability, a composite indicator of performance, ranged from 0.000 to 1.000, with the highest value (1.000) achieved at the same optimal condition. Overall, the results indicate that the optimal briquette formulation for high-quality performance was achieved at 0.5-part water hyacinth, 0.4-part sawdust, and 0.1-part rice husk, yielding superior density (0.93 g/cm^3), high shatter resistance (90.1%), efficient combustion (85.4%), and maximum desirability (1.000). This demonstrates the potential of hybrid biomass combinations to produce efficient, sustainable, and durable briquettes suitable for both domestic and industrial energy applications. Statistical analysis further confirmed the model's reliability and predictive accuracy. The model yielded a mean briquette quality of 43% with a standard deviation of 0.3086, indicating low variability and high consistency in experimental responses. The coefficient of determination (R^2 = 0.9562) and adjusted R^2 = 0.9289 show that over 95% of the variability in briquette quality was explained by the model. Additionally, the predicted R^2 (0.7560) closely aligns with the adjusted R^2, confirming good model predictability. The adequate precision value (15.3350) far exceeded the threshold of 4.0, indicating a strong signal-to-noise ratio, while the coefficient of variation (C.V.) of 0.7521% confirms high precision and reproducibility of results. The Analysis of Variance (ANOVA) further validated the statistical robustness of the model, showing it was highly significant (F = 34.97, $p < 0.0001$). The model sum of squares (16.65) accounted for most of the total variation (Cor. total = 17.41), confirming a strong model fit. Among

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the model terms, the linear mixture component (p = 0.0013) and binary interactions AB (p = 0.0003), AC (p < 0.0001), and BC (p = 0.0050) were all significant, with the AC interaction exerting the greatest influence (F = 129.16). The residual error (0.7618) was minimal, and the lack of fit (F = 0.1236, p = 0.7355) was not significant, confirming that the model adequately represents the experimental data. Collectively, these findings demonstrate that the developed model is statistically sound, reliable, and suitable for predicting and optimizing hybrid biomass briquette quality, providing a strong basis for sustainable bioenergy production.

Keywords: Briquette, Feedstock, Mix-ratio, Optimal blend, Briquetting machine, Water hyacinth, Biomass briquette, Sawdust, Rice husk, Density, Combustion efficiency, Desirability, Optimization.

Introduction

From time immemorial, man had always relied on energy for survival. Thus, energy is life because the great cycle of life depends on energy. Industrialization and rapid population growth has driven a parallel increase in global energy demand and waste generation. Continued reliance on fossil fuels raises concerns about greenhouse gas emissions, air pollution, and resource depletion, motivating the search for sustainable, low-emission energy alternatives. Biomass derived from agricultural and municipal waste represents a widely available, renewable resource that can address both energy and solid-waste management challenges when converted to densified fuels such as briquettes [1,2]. Briquetting describes the densification of loose biomass into compact blocks for the purpose of improving the fuel value, handling, transport, energy, density, and combustion performance. Different briquetting technologies have been developed over the years. They include the piston or ram presses, screw presses, and punching machines. Briquette quality such as density, mechanical strength, combustion rating, calorific value and ash content can be affected by compaction pressure, die geometry, feedstock particle size, and moisture. Thus, a well-designed machine modification and process optimization can improve product consistency and quality. Hybrid biomass briquettes describe the production of briquettes by blending two or more wastes. Combining two or more biomasses of the desired characteristics in proper blend ratio can ultimately improve the quality of briquettes. Aquatic plants such as water hyacinth with a botanical nomenclature (scientific name) Eichhornia crassipes are of particular interest because they are relatively abundant in freshwater bodies. Converting them into briquettes both provides energy and helps control invasive biomass. Studies have reported that carbonized water hyacinth can be blended directly with other biomass to produce briquettes for household and small-scale industrial use [3,4]. To identify optimal feedstock blend ratios including process settings, statistical experimental designs and output, response surface methodology (RSM) can be used. Response surface methodology (RSM) combines design techniques such as central composite and mixture with ANOVA to quantify interactions effects and identifies parameters that maximize briquette quality such as calorific value and compressive strength and parameters that minimize undesired properties such as ash and moisture content. Recent experimental investigations applying RSM to briquetting show robust optimization results and provide a reproducible framework for process scale-up [5,6]. In this study, a modified briquetting machine is used to produce hybrid biomass briquettes derived from locally available wastes.

Aim and Objective

- To evaluate the effects of feedstock blend ratio, moisture content, particle size, and binder proportion on physical, thermal, and mechanical properties of briquettes.
- To use RSM to optimize process variables for improved calorific value, density, and compressive strength.
- To assess the potential of hybrid briquettes as a sustainable fuel alternative.

Literature Review

Briquetting is the process of converting biomass residues such as paper, sawdust, rice husk, plant leaves, and other organic wastes into solid fuels suitable for domestic and industrial applications. The machine that performs this transformation is known as a briquetting machine. Instead of posing environmental threats, the abundant biomass waste generated in many regions can be utilized as renewable energy sources. In line with this concept, developed a screw-type briquetting machine to produce briquettes using water hyacinth and wastepaper with cornstarch as binding agent. The study reported that the briquettes produced were efficient and suitable for household use [7]. According to, briquetting is a process of compressing agro-residues and sawdust materials with low bulk density into solid fuels [8]. The study delved into the assessment of integrated briquetting plant and reported that energy generation from biomass residues is economically feasible and environmentally sustainable. The integrated system converted dust particles into valuable energy products for both domestic and industrial purposes. A similar work involved the design and fabrication of a leaf log maker machine aimed at addressing the issue of deforestation resulting from excessive firewood use. The machine could compress dry leaves into compact logs that are useable as fuel. It could also process paper and wood waste. The system was designed to be compact, user-friendly, and environmentally sustainable, thus providing an affordable solution for waste-to-energy conversion [9]. The quest for alternative energy encouraged to design a low-cost, portable briquetting machine for production of biomass briquettes from sawdust and dry leaves [10]. Coffee husk and wheat flour served as binding agents. This research emphasized environmental sustainability. Recently, designed and constructed a commercial biomass briquetting machine suitable for rural communities, using sawdust as the feedstock and starch as the binder [11]. The research reported that the physical and combustion characteristics of briquettes were strongly influenced by the type and concentration of the binder (binding material). The researchers further noted that although briquetting technology is still emerging in most African countries, it has achieved significant development in Europe and America. They identified key factors influencing the adoption of briquetting technology as residue availability, technological accessibility, and market demand for briquettes. According to many developing countries generate large volumes of agricultural waste daily, which are typically disposed of through open-air burning, causing serious environmental pollution [12]. The study explored the use of agricultural residues such as rice husk, coffee husk, sawdust, groundnut shell, and cotton stalks for briquette production. Various technologies were employed to compact these materials at high temperature and pressure. The study highlighted the advantages of biomass briquetting and analyzed the key factors influencing briquette quality, including a comparative analysis of biomass and coal briquettes. In research, provided a comprehensive theoretical review of biomass briquetting, emphasizing the challenges associated with conventional energy supply and the potential of biomass as a renewable energy source [13]. The study outlined the advantages of briquetting, including environmental benefits and energy decentralization, and identified parameters such as moisture content and temperature as critical to briquette quality. The author concluded that biomass briquetting represents a viable pathway towards sustainable energy utilization. In another study, designed and fabricated a hydraulically operated briquetting machine capable of producing briquettes from agricultural wastes such as rice husk, sawdust, and sugarcane [14]. The machine consisted of a frame, hydraulic jack, piston, and cylinder that served as the compaction chamber. Experimental results revealed that binder concentrations of 15% and 25% yielded briquettes with optimal strength and combustion characteristics suitable for both domestic and industrial use. The diversity of biomass materials implies that different feed stocks require distinct briquetting approaches. Consequently, the design of a briquetting machine largely depends on the type of material to be processed. In many African nations, particularly Nigeria, rapid population growth has exerted significant pressure on conventional fuel supply, leading to an increased reliance on firewood for domestic energy needs. This practice has accelerated deforestation, which in turn contributes to soil erosion and ecological imbalance. To mitigate this challenge designed a briquetting machine that utilized grass as the primary raw material [15]. The machine's operation involved three stages including pulverization, compaction, and extrusion. The purpose of the study was to reduce domestic firewood use and mitigate deforestation through the development of an alternative biofuel source. In most developing countries, approximately 80% of the population resides in rural areas, where energy consumption is principally associated with cooking and space heating. Although agricultural residues such as rice husk, groundnut shell, rice straw, wheat straw, sawdust, and coconut fibers are abundant, these resources are often unexploited, underutilized or inefficiently used. Recognizing this issue, investigated screw design parameters suitable for the conversion of biomass waste into energy [16]. The study emphasized the role of screw extrusion in enhancing briquette quality and efficiency. Four different screw types were fabricated based on design principles adapted from the Institute of Energy, Vietnam. In Pakistan, fossil fuels such as coal and petroleum dominate the national energy mix, especially in semi-urban areas. Industrial sectors including manufacturing, food processing, and pharmaceuticals predominantly rely on coal for thermal energy, resulting in substantial greenhouse gas emissions. Additionally, firewood use among rural communities leads to inefficient combustion and air pollution. To address these challenges, designed and fabricated a biomass extruder capable of producing 50mm-diameter briquettes [17]. The system featured a power screw and a slotted tapered die heated by electric elements. During operation, ground biomass passed through a hopper and compressed by a motor-driven screw rotating at 300rpm. The design provided a viable alternative to fossil fuel dependence by generating clean, compact biomass briquettes. The Philippines, known for its vast agricultural resources, generates large volumes of biomass waste from crops such as rice, coconut, and forest products. These materials represent significant potential for renewable energy generation, particularly for domestic cooking and small-scale industrial applications. To harness this potential, developed a compact briquetting machine with a central-hole extrusion design. This structural feature facilitated efficient, smokeless combustion [18]. The machine could produce sixteen briquettes per production cycle, demonstrating the feasibility of high-capacity briquetting in agricultural economies. A sawdust briquetting machine capable of converting waste into solid fuels was designed and presented. The system's major components included a hopper, housing unit, barrel, die, and shaft. The machine achieved a production capacity of 9kg/hour, demonstrating that waste-to-energy conversion can also generate employment and promote sustainable livelihoods [19]. Recently, developed a screw-press briquetting machine using locally sourced mild steel due to its rigidity, machinability, and availability [20]. The machine produced briquettes from sawdust using cassava-starch as a binder. The study found that briquettes with central holes exhibit improved combustion efficiency. Comparative evaluation revealed that the machine's performance was superior to many locally manufactured briquetting systems. In many developing African countries, the direct combustion of biomass such as rice husk, palm kernel shells, and groundnut shells often results in low thermal efficiency and increased greenhouse gas emissions [21]. The inefficient burning of these materials not only wastes potential energy resources but also contributes significantly to environmental pollution. Furthermore, the bulkiness and low density of raw biomass residues present challenges in transportation and handling, limiting their usability as a reliable energy source [22]. Briquetting, however, offers a sustainable solution to these limitations. As reported in the study, briquetting encompasses the densification or compression of loose biomass particles into compact, rigid blocks of regular shape, with or without the addition of binding agents [23]. Through the briquetting process, low-density biomass is transformed into dense, energy-rich briquettes that are easier to transport, store, and combust. This process also increases the calorific value of the fuel and reduces the emission of harmful gases during combustion [24]. In a study, Chilanga designed and fabricated a manually operated agro-waste briquetting machine with a production capacity of 10tones/day using locally available materials [25]. The machine consisted of a compacting chamber with twenty molds, each equipped with dies, pistons, and ejectors. It could produce twenty briquettes per batch. The development of such system demonstrated that low-income communities could adopt low-cost, manual briquetting technologies to transform agricultural residues into usable fuel sources [26]. Agricultural residues such as rice husks, groundnut shell, sawdust, cotton stalks, and coffee husks are abundant in Africa but are often inefficiently burned in open air, releasing carbon monoxide and particulate matter that damage the ecosystem [27]. The conversion of these residues into briquettes mitigates many of these problems via the reduction of environmental pollution, improving storage and handling, and providing a renewable, non-polluting substitute for fossil fuel [28]. A study presented the designed and construction of a screw extrusion briquetting machine for sawdust, operating at a rate of 7kg/h [29]. The investigation highlighted the significant effects of moisture content and binding agents on the mechanical and combustion properties of the briquettes produced. Sawdust is a major byproduct of wood processing industries, often disposed of as waste, thereby constituting environmental hazard and breeding ground for pests and reptiles [30]. The strategic intent of this current study is to adopt briquetting technology to transform such byproducts into useful energy for domestic and industrial applications.

Methodology

Research procedure overview

This study focuses on the experimental investigation and optimization of feedstock blend ratio for good quality briquettes production. The hybrid biomass blend ratio optimization was carried out by means of design expert software version 13, adopting the mixture design technique to determine the most suitable blend ratio for the formulation of briquettes with high quality in terms of density, shatter index, calorific value, low ash content, mechanical firmness and a superior aesthetic value. An optimized feedstock blend ratio of 0.5kg of water hyacinth, 0.4kg of saw dust and 0.1kg of rice husk was mixed with starch (binder), providing a uniform feedstock for a manually operated piston-type briquetting machine capable of producing 24 cylindrical-shaped briquettes at a time. Ultimately, the research process involves feedstock characterization, selection, preparation, production and performance evaluation of the briquettes produced.

Feedstock assessment

Hybrid biomass briquette is derived from the mix of two or more biomasses in the most suitable blend-ratio for superior quality briquettes. Selecting the right feedstock blend is crucial to producing briquettes that maximize the desired briquette qualities such as mechanical strength, shatter index, density and calorific value. Feedstock assessment encompasses identifying the most suitable biomass via a comprehensive analysis of the physical and chemical properties such as moisture content, heating value and ass content. It also involves cost implication consideration, availability and the proximity of feed stocks to the desired location.

Feedstock sourcing, pretreatment and storage: The characterization of Water Hyacinth (WH), Sawdust (SD), and Rice Husk (RH) reveals notable variation in feedstock sources and preparation. Water hyacinth with high moisture content range of 70% –90% was obtained from freshwater bodies near riverine communities and initially sun-dried to reduce the excess moisture before further drying. Dried specimen of sawdust and rice husk were obtained from wood processing plant and rice mill plant respectively. Furthermore, all samples were oven-dried at 105 °C until constant weights were achieved. The dried biomass materials were crushed down and sieved. Uniform particle size of 0.5–2.0 mm was obtained as the feedstock materials which were stored in airtight containers at room temperature. Details are presented in table 1 [31,32].

Feedstock proximate and ultimate analysis: The proximate and ultimate analyses of Water Hyacinth (WH), Sawdust (SD), and Rice Husk (RH) reveal significant variances in their fuel characteristics. The feedstock materials displayed a moisture content range of 8–12%. This range is suitable for elevated quality briquettes with high combustion efficiency. Rice husk was observed to have the highest ash content of 15–25%, moderate range of 8–20% was observed in water hyacinth and the lowest range of 0.5–3% in saw dust, signifying that less residual ash would be produced by saw dust. Volatile matter was relatively high in all samples (60–85%), suggesting good ignition properties. Fixed carbon content ranged from 8–20%, which contributes to longer burning duration. However, the

Description	Water Hyacinth (WH)	Sawdust (SD)	Rice Husk (RH)
Sources	Aquatic weed from water bodies	Residue from wood processing	By-product from rice milling
State of Collection	Fresh (high moisture 70–90%)	Dry	Dry
Pretreatment	Air-dried, then oven-dried at 105 °C to constant weight	Oven-dried at 105 °C	Oven-dried at 105 °C
Particle size (mm)	0.5–2.0	0.5–2.0	0.5–2.0
Storage method	Airtight container at room temperature	Airtight container	Airtight container

Table 1: Biomass materials sourcing and pretreatment.

ultimate analysis revealed that carbon content was highest in sawdust (45–50%), indicating better calorific potential compared to water hyacinth and rice husk. Hydrogen values ranged between 4–6%. Generally, nitrogen and sulphur contents were less than 2% (low), reducing the emission of harmful gases. Oxygen content spanned from 43% to 50%, enhancing good quality combustion and efficiency. Saw dust with a higher heating value (HHV) which ranged from (12–20) MJ/kg, showed its suitability as the main component in briquette production. Ultimately, the analysis showed that a good blend ratio of feedstocks can balance and cover up individual weaknesses and improve briquette performance [33]. Table 2 presents the details.

Comparative analysis of cellulosic composition, thermal behaviours, and functional properties of feedstock: Table 3 presents the structural, thermal, and chemical properties of Water Hyacinth (WH), Sawdust (SD), and Rice Husk (RH), which influence their performance as briquetting feed stocks. Combustion efficiency and binding can be affected by the key components including cellulose, hemicellulose, and lignin which varied across the materials. Sawdust showed the highest cellulose, spanning the range of 30–50% and lignin 15–30% contents, indicating strong structural integrity and higher energy yield. Water hyacinth contained lower cellulose of 20–35% and lignin 5–15%, reflecting its weaker and less fibrous structure. Rice husk had moderate cellulose of 30–45% and lignin 10–25% with a high silica content, which can affect ash formation during combustion. Bulk density values ranged between 0.10–0.35 g/cm^3, with sawdust showing slightly higher density, which supports better compaction during briquetting. The pH values of 6.0–8.0 across all samples indicate neutral, suitable for stable combustion. Thermogravimetric analysis (TGA) indicated char yields of 10–30% over a decomposition temperatures range of 250°C–380°C, suggesting similar thermal degradation behavior among the materials. FTIR analysis showed the presence of characteristic functional groups such as [–OH], [C=O], and [C–H], confirming the presence of cellulose, hemicellulose, and lignin structures typical of lignocellulosic biomass. Ultimately, sawdust showed superior structural and thermal stability, while water hyacinth and rice husk provided balancing characteristics [34].

The comparative assessment of the relationship between Feedstock properties and briquette quality: Table 4 highlights the effects of feedstock properties on the performance and quality of briquettes produced from Water Hyacinth, Sawdust, and Rice Husk. Moisture content significantly affects briquette density and heating value. Optimally, a range of 6–12% guarantees effective binding and combustion. Specifically, high ash content in rice husk, reduces heating value and generates excessive residue, emphasizing the need for moderate blending. Lignin, abundant in sawdust provides natural binder which improves briquette overall strength and durability. Volatile matter enhances ignition. Water hyacinth and rice husks contribute to easier ignition of the briquette. Fixed carbon content supports stable and extended burning, with sawdust providing the greatest results. However, high silica content in rice husk can lead to abrasive ash and clinker formation during combustion. Bulk density influences briquette compactness and energy density, with an ideal range of 0.25–0.40 g/cm^3. Calorific value, which represents the overall energy capacity, is highest and lowest in sawdust and water hyacinth respectively. Expert design software determined the best blend ratio which can combine with a suitable binder (starch) to ensure improved briquette

Property	Method	Water Hyacinth (WH)	Sawdust (SD)	Rice Husk (RH)
Moisture Content (%)	Oven drying (105°C)	8–12	8–10	8–12
Ash Content (%)	Muffle furnace (550 °C)	8–20	0.5–3	15–25
Volatile Matter (%)	ASTM D3175	60–75	70–85	65–75
Fixed Carbon (%)	By difference	10–20	10–20	8–18
Carbon (C, %)	CHNS analyzer	40–45	45–50	40–48
Hydrogen (H, %)	CHNS analyzer	5–6	5–6	4–5
Nitrogen (N, %)	CHNS analyzer	0.5–2	0.1–0.5	0.2–1
Sulphur (S, %)	CHNS analyzer	0.1–0.3	0.05–0.1	0.05–0.1
Oxygen (O, %)	By difference	46–50	43–48	46–50
Higher Heating Value (MJ/kg)	Bomb calorimeter	12–16	16–20	13–16

Table 2: Proximate and Ultimate Analysis of Biomass Feed Stocks Used for Briquetting.

Property	Method	Water Hyacinth (WH)	Sawdust (SD)	Rice Husk (RH)
Cellulose (%)	Van Soest/NREL method	20–35	30–50	30–45
Hemicellulose (%)	Van Soest/NREL method	10–25	15–35	10–25
Lignin (%)	Van Soest/NREL method	5–15	15–30	10–25
Silica Content in Ash (%)	XRF/ICP-AES	Low–Moderate	Low	High (major component
Bulk Density (g/cm³)	Volumetric method	0.10–0.30	0.15–0.35	0.10–0.30
pH (1:10 slurry)	pH meter	6.5–7.5	6.0–7.0	6.5–8.0
TGA Char Yield (%)	TGA analysis	10–25	15–25	15–30
Main Decomposition Temp (°C)	TGA/DTG	250–370	280–380	270–370
FTIR Major Bands	–OH, C=O, C–H, aromatic rings	Similar for all	Similar for all	Similar for all

Table 3: Structural, Thermal, and Chemical Characterization of Biomass Feed stocks for Briquetting

Property	Effect on Briquetting	Remarks
Moisture	Too high reduces density & HHV; too low reduces binding	Optimum 6–12%
Ash	High ash lowers heating value & increases residue	RH has highest ash; blend moderately
Lignin	Acts as natural binder during compaction	SD rich in lignin, good for strength
Volatile Matter	Affects ignition and combustion rate	WH and RH help in easy ignition
Fixed Carbon	Determines char yield and steady burn	SD helps maintain longer burn
Silica	Causes abrasive ash and clinker formation	Silica content of RH is high; needs careful handling
Bulk Density	Influences briquette density and energy content	Blend to achieve 0.25–0.40 g/cm³
Calorific Value	Indicator of energy potential	SD highest HHV; WH lowest
Blending Strategy	Combine WH, SD, RH and a Binder(starch)	Adopting the optimized ratio by the design software

Table 4: Influence of Key Physicochemical Properties on Briquetting Performance.

S/N	Selection Criterion	Description / Measurement Basis	Desired Range / Condition	Relevance to Briquetting Performance
1	Availability and Cost	Ease of sourcing, seasonal abundance, transport cost	Readily available, low-cost, sustainable	Ensures continuous feed supply and reduces production cost
2	Moisture Content (%)	Measured by oven drying at 105 °C to constant weight	6–12 % (for briquetting)	Optimum moisture enhances compaction and prevents cracking or steam pressure during pressing
3	Ash Content (%)	Determined by muffle furnace at 550 °C	Less than 10–12 %	Low ash gives higher heating value and reduces slagging during combustion
4	Volatile Matter (%)	By proximate analysis	60–80 % desirable	High volatile matter supports easy ignition and better combustion
5	Fixed Carbon (%)	By difference [100 – (M + VM + Ash)]	10–25 %	Increases char yield and steady burning rate
6	Higher Heating Value (MJ/kg)	Measured using bomb calorimeter	At least 15 MJ/kg	Determines the energy potential of the briquette
7	Lignin Content (%)	Estimated by Van Soest/NREL method	At least 10–18%	Provides natural binding property and improves briquette strength
8	Particle Size (mm)	Sieving or grinding measurement	0.5–2.0 mm	Uniform small particles improve packing density and bonding
9	Bulk Density (g/cm³)	Ratio of mass to volume after gentle tapping	0.18–0.35 g/cm³	Affects feed handling, compaction efficiency, and briquette density
10	Silica Content / Abrasiveness	Determined by XRF or ICP-AES of ash	As low as possible (less than 15 % of ash)	High silica causes equipment wear and clinker formation during combustion
11	pH and Electrical Conductivity	1:10 biomass–water extract	pH rang of 6–8; and low EC	Neutral pH prevents corrosion and affects ash reactivity
12	Environmental and Handling Factors	Odour, toxicity, biodegradability, legal/ethical considerations	Safe, non-toxic, environmentally beneficial	Ensures safety, sustainability, and public acceptance
13	Processing Ease	Ease of drying, milling, blending	Should require minimal pre-treatment	Reduces energy input and overall production cost

Table 5: Feedstock selection criteria.

strength, combustion efficiency, and sustainability [35].

Feedstock selection criteria: Table 5 outlines the key selection criteria that determine the suitability of biomass feed stocks for briquette production. The table underscores the importance of feedstock availability for continuous production and low transportation cost for reduced operational expenses. The moisture content should range between 6–12%, as excessive moisture reduces briquette density and causes cracking, while too little moisture hampers good compaction. Ash content below the range of 10–12% improves heating value and combustion efficiency as lower ash content minimizes slagging and residue formation. Volatile matter of 60–80% facilitates easy ignition, while fixed carbon of 10–25%, supports prolonged burning and higher char yield. A higher heating value of at least 15 MJ/kg indicates strong energy potential. Lignin content of 10–18% acts as a natural binder and improves briquette cohesion and mechanical strength. Other important factors include particle size of 0.5–2.0mm for better packing and bonding, bulk density 0.18–0.35 g/cm^3 for efficient compaction, and low silica content of less than 15% is essential for the reduction of abrasion and clinker formation. A near-neutral pH (power of hydrogen) range of 6–8 and low electrical conductivity ensure corrosion-free equipment operation and stable ash behaviour. Additionally, environmental factors such as odour, safety, and biodegradability influence public acceptance and sustainability, while ease of processing minimizes pre-treatment costs. Ultimately, these factors ensure optimal briquette performance, energy efficiency, and ecological compatibility [36,37].

Materials and equipment

- Water Hyacinth (Eichhornia crassipes) collected from water bodies
- Saw Dust obtained from wood processing plant (sawmill)
- Rice Husk obtained from a local rice processing plant
- Starch obtained as byproduct of processed cassava
- A fabricated manual piston-type briquetting machine

for compacting feedstock to solid briquettes

- Weighing balance for weight measurement
- Grinder for feedstock reduction
- Sieve for sieving and particle size control
- compression testing machine for strength testing

Feed stock preparation

Biomasses including water hyacinth, saw dust and rice husk were obtained from water bodies, wood processing plant and rice processing mill respectively. They were then left to dry in the sun for about 72 hours before further drying in oven. They were later crushed down by means of grinder and sieved to reduce the particle size to about 0.5mm to 2.0 mm for uniformity and proper bonding during compaction. Feedstock selection and suitability were based on the criteria shown in table 2, which include availability, cost, ash content, volatile matter, fixed carbon, and calorific value. The desired ranges were maintained within acceptable limits of moisture content of 6–12%, ash content less than 12% and heating value greater than 15 MJ/kg.

Experimental design and optimization

Optimization of the feedstock blend ratios was carried out using Design Expert 13 software, adopting mixture design approach. Three components such as water hyacinth (A), sawdust (B), and rice husk (C) served as independent variables, constrained to sum up to 1kg (100%). Responses such as density, shatter index, calorific value, average briquette quality and others were obtained from feedstock blend of 0f 0.5kg of water hyacinth, 0.4kg of saw dust and 0.1kg of rice husk which occurred at run 11, amounting to average briquette quality of 43%.

Briquette production

After the preparation of the feedstock which contains a homogeneous mixture of water hyacinth, saw dust, rice husk and water including a binder (cassava starch 10% by weight), the mixture was fed into the manual piston briquetting machine. A compacting pressure of 2.5Mpa was applied by means of a jack which compressed a set of 24 pistons down the array of cylinders containing the feedstock. The compacted feed stocks (briquettes) were sun-dried for about 6 days until constant weight was achieved before testing. A photograph in the figure 1 below captures the loading of feedstock into the fabricated briquetting machine.

Briquette performance evaluation

The briquette produced from the optimal blend ratio of 0.5:0.4:0.1 of water hyacinth, sawdust, and rice husk respectively exhibited excellent physical and combustion properties. The briquette had high density of 0.93 g/cm^3 and strong mechanical durability including shatter index of 90.1%, indicating good handling strength. The briquette also showed efficient combustion with a high combustion rate of 85.4% and low ash content which approximately ranged from 5% to 7%, signifying clean burning performance. Overall, these results demonstrate that hybrid briquette possesses desirable qualities for effective and sustainable fuel use. Details are shown in table 6.

Data analysis

Experimental data were analyzed statistically using ANOVA in Design Expert software to evaluate the effect of each component on briquette quality parameters. Regression models were developed to predict optimal mixture compositions. Graphical outputs such as 3D surface plots and contour maps were used to visualize the relationships among the factors and responses [39].

Results and Discussions

This session explores the results and discussions of biomass briquettes production focusing on the optimization of feedstock mix-ratio as the key parameter and the qualities of the resulting briquettes.

Experimental design matrix result

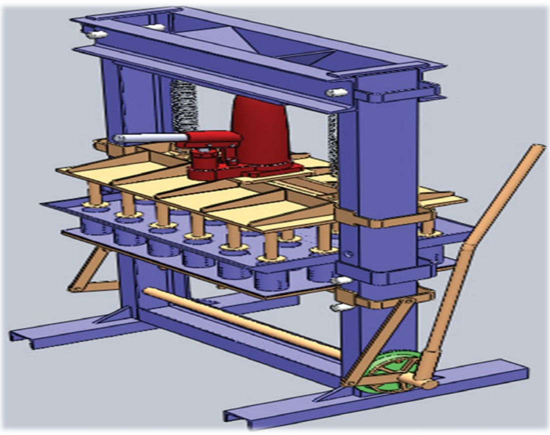
The experimental data obtained by means of design expert software are presented in table 7. The data shows the effect of the mix-ratios of water hyacinth, sawdust, and rice

Properties	Evaluation Techniques	Process	Observations
Density	Mathematical	Density = Mass / Volume	0.93 g/cm³
Moisture Content	Oven drying	Dried at 105 °C to constant weight	Low residual moisture content (≈ 8–10%), indicating proper drying and efficient combustion.
Calorific Value	Using bomb calorimeter	Burnt and heat released measured	High energy value (≈ 18–20 MJ/kg), showing good heating potential.
Volatile Matter and Fixed Carbon Ratio	Analytical	Determined by proximate analysis	Volatile matter ≈ 65–70% and fixed carbon ≈ 20–25%, suitable for stable and sustained combustion.
Ash Content	Combustion	Burnt in muffle furnace at 550 °C	Low ash residue (≈5–7%), indicating clean burning fuel.
Compressive Strength	Using a universal testing machine	Subjected to compressive pressure	High structural integrity, briquettes remained intact under load.
Shatter Index	Physical	Allowed to fall from a height of 1 m	90.1%, showing good resistance to mechanical breakage and impact.
Combustion Rate	Combustion	Determined through mass loss over time	85.4% combustion efficiency, indicating efficient burning with minimal smoke.
Testing adopted ASTM D3173–D3175 and ASTM E711–87 standards [38]			

Table 6: Briquette performance assessment.

BRIQUETTE QUALITY									
STD	RUN	A: Water Hyacinth	B: Saw Dust (kg)	C: Rice Husk (kg)	Density (g/cm³)	Shatter Index (%)	Combustion Efficiency (%)	Average Briquette Quality (%)	Desirability
12	1	0.4	0.4	0.2	0.90	88.3	81.6	40.95	0.666
10	2	0.433	0.333	0.233	0.82	90.0	82.1	41.72	0.791
3	3	0.4	0.3	0.3	0.91	87.5	80.4	40.24	0.550
13	4	0.4	0.3	0.3	0.85	83.1	75.3	36.87	0.000
7	5	0.5	0.3	0.2	0.89	85.4	79.5	39.17	0.375
14	6	0.5	0.4	0.1	0.88	86.5	78.9	39.35	0.405
8	7	0.4	0.4	0.2	0.90	88.3	81.6	40.95	0.666
5	8	0.5	0.2	0.3	0.88	86.5	78.9	39.35	0.405
2	9	0.4	0.4	0.2	0.90	88.3	81.6	40.95	0.666
6	10	0.3	0.4	0.3	0.93	90.2	85.1	42.92	0.987
4	11	0.5	0.4	0.1	0.93	90.1	85.4	43.00	1.000
11	12	0.5	0.3	0.2	0.85	83.1	75.3	36.87	0.000
9	13	0.4	0.3	0.3	0.89	85.4	79.5	39.17	0.375
1	14	0.5	0.3	0.2	0.88	86.5	78.9	39.35	0.405

Table 7: Experimental design matrix results.



Solid work model of briquetting machine

Loading feedstock into briquetting machine

Feedstock and samples of briquettes produced

Figure 1: Solid work model, fabricated briquetting machine, feedstock and samples of briquettes produced.

husk on hybrid biomass briquettes qualities such as density, shatter index, combustion efficiency and desirability. Each of these parameters mirrors the mechanical and thermal characteristics of the briquettes across material compositions variations. The feed stocks were combined to a constrained sum of one unit to ensure controlled monitoring and analysis of their influence on briquette quality. From the results, it is observed that the optimum briquette quality occurred at run 11, with a corresponding blend ratio of 0.5kg of water hyacinth, 0.4kg of sawdust, and 0.1kg of rice husk. At this composition, the briquette recorded a density of 0.93 g/cm^3, a shatter index of 90.1%, and a combustion efficiency of 85.4%. These metrics translated to an average briquette quality of 43%, the highest among all the experimental runs, and a desirability index of 1.000, indicating a perfectly optimized combination of mechanical and combustion characteristics. Relatively, the high density obtained at this blend suggests excellent compaction, which improves handling and storage. Also, the high shatter index confirms the briquette's strong mechanical integrity and resistance to breakage, while the combustion efficiency shows an effective conversion of the briquette into heat energy with minimal residue. The optimum performance observed at run 11 can be attributed to the synergistic interaction of the three biomasses. Water hyacinth, used at 0.5kg (50%), provided satisfactory binding characteristics and volatile matter content, enhancing consistency during compaction and ignition during burning. Sawdust, at 0.4kg (40%), contributed to lignocellulosic material that reinforced the briquette's structure and supported stable combustion. Rice husk metric of 0.1kg (10%), added firmness and improved the briquette's durability via its silica-content in a regulated amount for less ash formation. The equilibrium of the mix-ratios produced a perfect hybridization that maximized mechanical and thermal efficiency. Comparatively, runs that indicate lower-quality briquettes occurred at 4 and 12 with significantly reduced density and combustion efficiency, leading to average briquette qualities of 36.87% and 0.00 desirability. Intermediate runs, such as 1, 3, 5, 8, 9, 13, and 14, recorded average briquette qualities which spanned between 39% and 41%, signifying tolerable but suboptimal results. Run 10, with an average quality of 42.92% and a desirability of 0.987, represents nearly optimum performance. However, the slight variation in component ratios led to slightly lower performance. The optimum blend ratio of 0.5:0.4:0.1 is the most suitable mix for producing high-quality briquettes that combine strength, durability, and efficient combustion. The mix produces briquettes that possess high energy density, burn cleanly with negligible residue, and can withstand handling and transportation stress. This composition therefore represents the most balanced and efficient formulation for hybrid biomass briquette production, offering a feasible path for sustainable energy generation from agricultural and aquatic biomass wastes.

Optimum feedstock blend

A blend ratio of 0.5: 0.4: 0.1 for components A (Water Hyacinth), B (Saw Dust), and C (Rice Husk), produced briquette that exhibited high quality and performance. The density was 0.93 g/cm^3, signifying a compact briquette. It achieved a shatter index of 90.1%, demonstrating strong mechanical toughness, and a combustion efficiency of 85.4%, showing excellent burning characteristics. The average briquette quality was 43.00%, at a desirability value of 1.000, signifying the optimal (desirable) production condition across the experimental runs. Table 8 presents the optimal briquette production conditions.

Model fit statistics and summary

Table 9 shows the summary of the model fit statistics. The statistical analysis shows a high model accuracy with an R^2 value of 0.9562 and an adjusted R^2 of 0.9289, indicating that the model is significant and consistently explains the data variability. The low coefficient of variation of 0.75% and high adequate precision of 15.3350 confirm the model's precision, consistency, and strong predictive capability as shown by Predicted R^2 value of 0.7560. The R^2 value of 0.9562 and adjusted R^2 value of 0.9289 and quite close and less than 0.2, indicating that the model can be used to navigate the design space.

Model's Analysis of variance [ANOVA]

The analysis of variance (ANOVA) indicates that the overall model is highly significant with F value equals 34.97 and P value less than 0.0001. These metrics suggest that the blend ratios of the components have a substantial effect on briquette quality. Among the interaction terms, the AC interaction (Water Hyacinth × Rice Husk) showed the most dominant influence with an F-value of 129.16 ($p < 0.0001$), followed by AB (Water Hyacinth × Sawdust) and BC (Sawdust × Rice Husk), both of which were also significant. The linear mixture term contributed moderately as indicated by metrics of $F = 16.93$ and $p = 0.0013$, showing that individual component effects are important but less impactful than their interactions. The lack of fit was not

Parameter	Value	Remarks
Run Number	11	Experimental identification
Standard Order	4	Design Expert reference order
Blend Ratio (A: B:C)	0.5: 0.4: 0.1	Water Hyacinth: Saw Dust: Rice Husk
Density (g/cm^3)	0.93	High compactness and structural strength
Shatter Index (%)	90.1	Excellent mechanical durability
Combustion Efficiency (%)	85.4	High energy conversion efficiency
Average Briquette Quality (%)	43.00	Overall quality performance index
Desirability	1.000 (maximum)	Indicates optimal production condition

Table 8: Optimal briquette production conditions details.

Std. Dev.	0.3086	R^2	0.9562
Mean	41.03	Adjusted R^2	0.9289
C.V. %	0.7521	Predicted R^2	0.7560
		Adeq. Precision	15.3350

Table 9: Summary of model.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	16.65	5	3.33	34.97	< 0.0001	significant
Linear Mixture	3.22	2	1.61	16.93	0.0013	
AB	3.45	1	3.45	36.26	0.0003	
AC	12.30	1	12.30	129.16	< 0.0001	
BC	1.39	1	1.39	14.64	0.0050	
Residual	0.7618	8	0.0952			
Lack of Fit	0.0132	1	0.0132	0.1236	0.7355	not significant
Pure Error	0.7486	7	0.1069			
Cor Total	17.41	13				

Table 10: ANOVA.

Component	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
A-WATER HYACINTH	55.14	1	1.56	51.54	58.74	50.70
B-SAW DUST	43.97	1	1.56	40.37	47.56	50.70
C-RICE HUST	49.71	1	1.44	46.40	53.03	37.70
AB	-26.24	1	4.36	-36.28	-16.19	48.40
AC	-45.75	1	4.03	-55.03	-36.47	30.68
BC	-15.40	1	4.03	-24.69	-6.12	30.68

Table 11: Coefficient in terms of coded factors.

4.6. Two/three-dimensional contours of briquette yields and plots

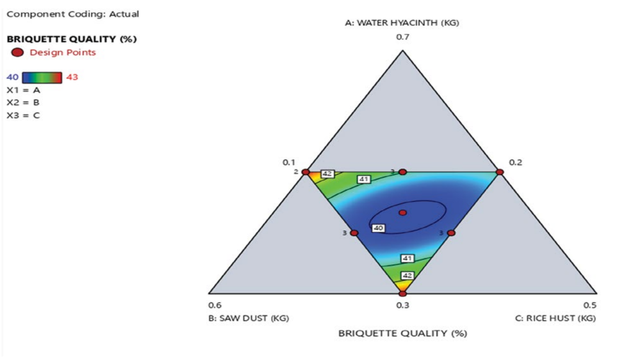


Figure: 2D Contour

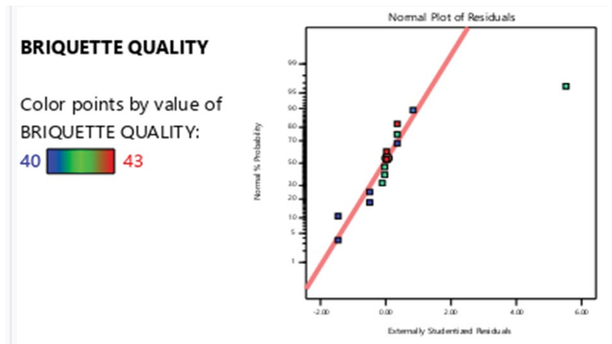


Figure: Norma plot versus residuals

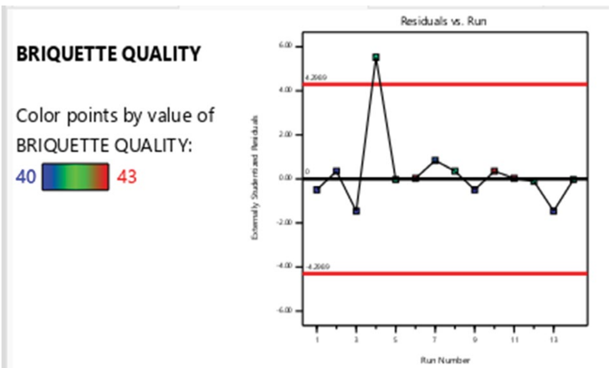


Figure: Residual versus run plot

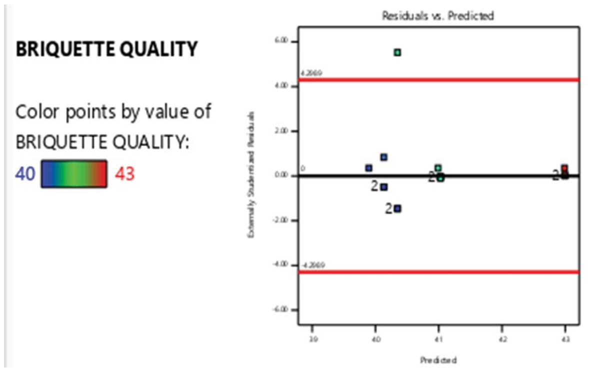


Figure: Residual versus predicted plot

Figure 2: 2D contour and plots.

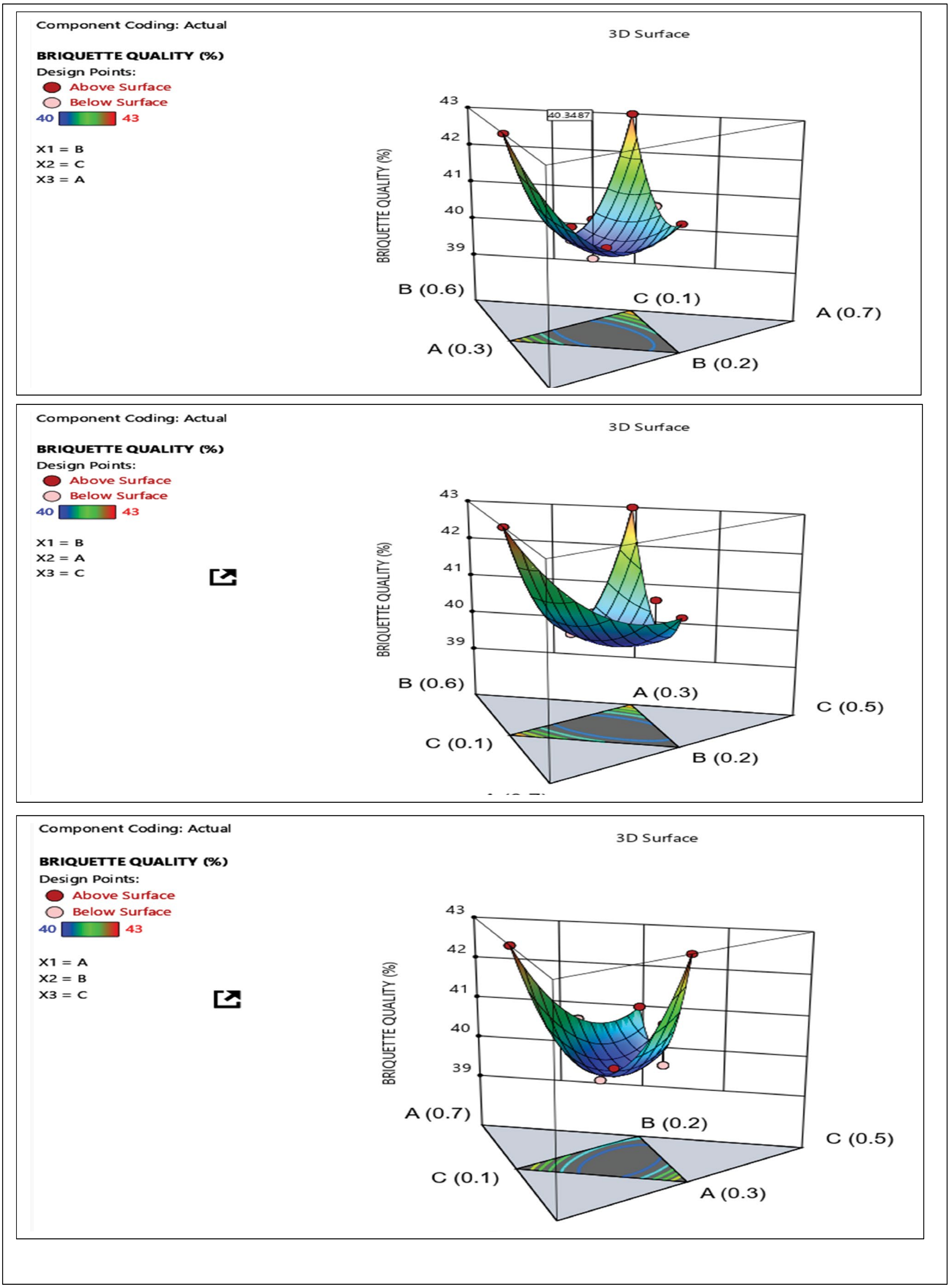


Figure 3: 3D Surface plot.

significant (p =0.7355), indicating that the model adequately fits the experimental data without systematic errors. Details are presented in table 10.

Factors interaction interpretation

The coefficient evaluations reveal that water hyacinth (55.14) has the highest positive contribution to briquette quality, followed by rice husk (49.71) and sawdust (43.97), indicating that higher proportions of water hyacinth and rice husk improve performance. The negative interaction coefficients (AB = −26.24, AC = −45.75, and BC = −15.40) suggest that combining these components in excess reduces briquette quality due to unfavorable interactions. The AC interaction (Water Hyacinth × Rice Husk) shows the strongest negative effect, implying that their proportions must be carefully balanced to achieve optimal results. The relatively high VIF values indicate strong correlations among the variables, which is expected in mixture experiments where component proportions are interdependent. Table 11 presents the details.

Coded equation

Briquette quality (%) = +55.14A +43.97B +49.71C -26.24AB -45.75AC -15.40BC

Actual equation

Briquette quality (%) = +103.13063water hyacinth +72.62839saw dust +133.20355rice husk-163.97767water hyacinth *saw dust -285.93244water hyacinth*rice husk.

Two/three-dimensional contours of briquette yields and plots

Figures 2 and 3

Comparative analysis

Comparatively, the key finding of this study closely aligns with the research results established by Okwu and Gbabo, who reported that the addition of fibrous residues such as sawdust increases briquette density and mechanical strength [40]. Similarly, the combustion performance obtained in this research constructively validates the research findings of Oladeji and Pushpa and Yadav who had noted that optimal moisture range of 6% to 12% and appropriate binder concentration can improve burning characteristics [41,42]. Ultimately, the use of mixture design method of design expert proved efficient in determining the interaction effects among biomass components, yielding statistically reliable predictive models and an optimal blend that offers sustainable, low-cost fuel for domestic and industrial applications.

Summary of Findings

- Density, shatter index, and combustion efficiency were strongly influenced by the mix-ratio proportions of the feedstocks.
- Sawdust contributed positively to all response variables due to its high lignin and fibrous structure.
- Excess water hyacinth reduced performance due to its low fixed carbon and high moisture content.

Conclusion

The study demonstrates that hybrid biomass briquettes produced from a blend of water hyacinth, sawdust, and rice husk can serve as a viable renewable energy alternative to conventional fossil fuels. The optimized composition produced briquettes with excellent mechanical strength, burning efficiency, and energy sustainability. The modified briquetting machine proved reliable and cost-effective, confirming that locally available agricultural and aquatic residues can be transformed into valuable solid fuels. Hence, the research validates that energy recovery from waste biomass through briquetting contributes significantly to sustainable energy development, environmental conservation, and rural economic empowerment [43].

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Conflict of Interest

The research declares no conflict of interests.

Author's Contribution

This research is the work of a single author

Data Availability Declaration

Data will be made available upon request.

References

1. Kpalo SY, Zainuddin MF, Manaf LA, Rosla AM (2020) A Review of Technical and Economic Aspects of Biomass Briquetting. Sustainability 12: 4609.
2. Roman K, Grzegorzewska E (2024) Biomass Briquetting Technology for Sustainable Energy Solutions: Innovations in Forest Biomass Utilization. Energies 17: 6392.
3. Carnaje NP, Talagon RB, Peralta JP, Shah K, Paz-Ferreiro J (2018) Development and characterisation of charcoal briquettes from water hyacinth (Eichhornia crassipes)-molasses blend. PLoS One 13: e0207135.
4. Midhun VC, Jayaprasad G, Anto A, Anish R (2023) Preparation and characterisation study of water hyacinth briquettes. Materials Today: Proceedings.
5. Nganko JM, Koffi EPM, Gbaha P, Toure AO, Kane M, et al. (2024) Modeling and Optimization of Compaction Pressure, Binder and Moisture for Briquette Quality using Box-Behnken (RSM). Heliyon 10: e25376.
6. Silas K, Mohammed HD, Mamza WJ (2021) Response Surface Methodology Optimization of Sawdust in Water Boiling Test. Journal of Chemistry Letters.
7. Okwu M, Chukwuekezie AC, Oji CS (2016) Development of Water Hyacinth Briquetting Machine. International Journal of Engineering and Applied Sciences 33: 40-50.
8. Gebrekidan T, Zeslase Y (2015) Design and Feasibility Study of an Integrated Briquetting Plant. International Journal of Energy Science and Engineering 3: 25-31.
9. Patel OS, Mahajan RV (2017) Design and Fabrication of a Leaf Log Maker Machine. International Journal of Engineering Research and Applications 7: 12-16.
10. Patil KV, Joshi NK (2016) Design and Fabrication of Portable Briquetting Machine. International Journal of Renewable Energy

Development 5: 211-217.

11. Obi OO, Onukwuli CC, Odo SI (2013) Design and Construction of an Appropriate Commercial Biomass Briquetting Machine for Rural Communities. Nigeria Journal of Technology 32: 475-482.

12. Maninder M, Rupinder RS, Singh N (2012) Utilization of Agricultural Residue for Briquette Production. Journal of Renewable Energy Review 6: 35-42.

13. Oladeji JT (2015) Theoretical Aspects of Biomass Briquetting. Energy and Environmental Research 5: 31-39.

14. Gbabo A, Mohammed JI, Okafor SB (2017) Design and Fabrication of a Hydraulically Operated Briquetting Machine. Agricultural Engineering International: CIGR Journal 19: 157-164.

15. Ajieh M, Okeke J, Uche SO (2016) Design and Fabrication of a Briquetting Machine Using Grass as Raw Material. Journal of Sustainable Energy Research 4: 112-118.

16. Nguyen AP, Tran L (2004) Optimization of Screw Design Parameters for Biomass Briquetting. Energy Conversion and Management 45: 2017-2024.

17. Mohammed T, Ahmed K, Bello SU (2016) Design and Fabrication of a Biomass Extruder for Briquette Production. International Journal of Mechanical and Industrial Engineering 6: 55-61.

18. Roda D (2017) Development of a Compact Briquetting Machine in the Philippines. Asia-Pacific Journal of Renewable Energy Technology 2: 33-39.

19. Arinola F, Olorunfemi PO, Ayeni EA (2013) Design of Sawdust Briquetting Machine for Domestic Fuel Production. Nigerian Journal of Renewable Energy 9: 15-21.

20. Ojo, Mohammed T (2015) Development of a Screw Press Briquette Making Machine Using Locally Sourced Materials. International Journal of Engineering and Technology Innovation 4: 185-192.

21. Chilanga M (2017) Design and Fabrication of a Manually Operated Briquetting Machine. University of Zambia Press, Lusuka.

22. Grover PC, Mishra SK (1996) Biomass Briquetting: Technology and Practices. Regional Wood Energy Development Programme.

23. Sharma SK, Mohanty R (2016) Briquetting of Agricultural Waste for Energy Generation: A Review. International Journal of Renewable Energy Research 6: 1325-2016.

24. Bhattacharya SC, Augustus DA, Leon M (2015) Sustainable Energy from Agricultural Residues via Briquetting Technology. Renewable Energy Review 9: 181–198.

25. Chilanga M (2017) Design and Fabrication of an Agro-Waste Briquetting Machine. Journal of Engineering and Applied Sciences 12: 185-190.

26. Kazi H (2011) Development of Small-Scale Biomass Briquetting Technology for Rural Energy Supply. Energy for Sustainable Development 15: 130-138.

27. Olorunnisola T (2010) Production of Fuel Briquettes from Waste Paper and Coconut Husk Admixtures. Journal of Engineering and Applied Sciences 5: 290-295.

28. Sidhu HS, Singh SK (2012) Evaluation of Briquetting Technologies for Agricultural Residues. International Journal of Biomass and Bioenergy 8: 77-84.

29. Pushpa PJ, Yadav P (2010) Design and Fabrication of Screw Extrusion Briquetting Machine for Sawdust. Journal of Renewable Energy Engineering 3: 44-51.

30. Arinola SA, Ojo TM, Mohammed T (2013) Design and Development of Sawdust Briquette Machine. Nigerian Journal of Mechanical Engineering 9: 55-62.

31. Adeleke A, Oladimeji TO, Hassan MB (2021) Physical and thermal characterization of biomass materials for fuel briquette production. Journal of Renewable Energy 170: 733-742.

32. Adekoya OS, Oladeji SO, Ogedengbe JO (2021) Characterization of selected agricultural residues for briquetting. Jornal of Appleid Science Environmental Management 3: 453-460.

33. Olatunji MS, Adeleke OA, Aremu KA (2022) Evaluation of physicochemical properties of selected biomass materials for briquette production. Journal of Energy Reports 8: 2304-2313.

34. Van Soest P, Robertson JB, Lewis BA (1991) Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. Journal of Dairy Science 74: 3583-3597.

35. Singh S, Gupta RC, Sharma NK (2022) Influence of feedstock properties on performance and emission characteristics of biomass briquettes. Energy Sources, Part A 44: 120-131.

36. Van Soest P, Robertson JB, Lewis BA (1919) Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. Journal of Dairy Science 74: 3583-3597.

37. NREL (2012) Determination of Structural Carbohydrates and Lignin in Biomass: Laboratory Analytical Procedure (LAP), NREL/TP-510-42618, Golden, CO, USA, 2012.

38. ASTM (2020) Standard Test Methods for Proximate Analysis of Coal and Coke by Macro Thermogravimetric Analysis. ASTM International 3173-3174.

39. Sidhu HS, Singh SK (2012) Evaluation of Briquetting Technologies for Agricultural Residues. Int J Biomass and Bioenergy 8: 77–84.

40. Okwu E, Onwualu JA, Ndirika IA (2016) Development of Biomass Briquetting Machine for Agricultural Residues. Nigerian Journal of Technology 35: 345-353.

41. Pushpa PJ, Yadav P (2012) Development and Testing of Briquetting Machine for Sawdust. Journal of Agricultural Engineering 47: 1-7.

42. Shyamalee S, Jayasuriya T, Dissanayake S (2015) Effect of Binder Type on Densification of Sawdust Briquettes. Energy Conversion and Management 90: 255-261.

43. Mohammed M, Ojo T, Lawal S (2016) Design and Fabrication of a Screw Extruder Briquetting Machine. Journal of Energy Technology 10: 55-63.

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