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# Cleaner cooking solutions: Optimizing biomass briquettes to replace charcoal and mitigate climate change in Tanzania

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ABSTRACT

In Tanzania, overreliance on charcoal and firewood for domestic energy has intensified deforestation and environmental degradation, creating an urgent need for sustainable biomass-based fuels. This study investigates the optimization of biomass briquettes produced from locally available agricultural residues (coconut shell, palm kernel shell, rice husk) and forest wastes as sustainable alternatives to charcoal. Carbonized feedstocks were blended with starch, molasses, or clay binders at varying ratios, and their proximate, energy, combustion, and mechanical properties were examined. The results demonstrated that feedstock type strongly influenced briquette performance, with coconut shell, palm kernel shell, and charcoal dust exhibiting high fixed carbon (>65 %), low ash (<10 %), and superior calorific values (6,299–6,737 kcal/kg). Among the binders, starch produced the best overall results, yielding briquettes with high shatter resistance (>93 %), rapid ignition (2–4 min), and steady burning rates (4–8 g/min). Molasses produced moderately strong briquettes with acceptable energy output but slightly higher ash content, while clay enhanced shape retention but reduced calorific value and prolonged ignition due to its non-combustible nature. The optimal starch loading was 20% for single-feedstock briquettes and 25% for blended systems. Blending rice husk with high-energy biochar at a 60:40 ratio improved calorific value (4,741–5,552 kcal/kg), reduced ash content (<20%), and enhanced mechanical durability, whereas the 50:50 blend exhibited moderate performance with lower energy density and higher ash levels, converting low-grade residues (rice husks) into efficient solid fuels. This research advances practical knowledge on optimizing feedstock blending and binder formulation to enhance biomass fuel quality, offering a scalable model for sustainable energy transitions in sub-Saharan Africa.

## Introduction

The rapid growth in global energy demand, coupled with limited access to modern and clean fuels in many developing regions, has

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**Nomenclature**

| | |
|---|---|
| ASTM | American Society for Testing Materials |
| BR | Burning rate |
| CC70 | Coconut shell 70 % and clay |
| CC75 | Coconut shell 75 % and clay |
| CHC70 | Charcoal dust 70 % and clay |
| CHC75 | Charcoal dust 75 % and clay |
| CHM75 | Charcoal dust 75 % and molasses |
| CHM80 | Charcoal dust 80 % and molasses |
| CHR40 | Charcoal dust and ricehusk 40 % |
| CHR50 | Charcoal dust and ricehusk 50 % |
| CHS75 | Charcoal dust 75 % and starch |
| CHS80 | Charcoal dust 80 % and starch |
| CM75 | Coconut shell 75 % and molasses |
| CM80 | Coconut shell 80 % and molasses |
| CR40 | Coconut shell and ricehusk 40 % |
| CR50 | Coconut shell and ricehusk 50 % |
| CS75 | Coconut shell 75 % and starch |
| CS80 | Coconut shell 80 % and starch |
| FC | Fixed carbon |
| GCV | Gross calorific value |
| SR | Shutter Resistance |
| IT | Burning Rate |
| M | Moisture content |
| WR | Water resistance |
| VM | Volatile matter |

reinforced the reliance on biomass as a renewable energy resource and the primary source of energy for domestic cooking. In Tanzania, charcoal and firewood dominate, with urban households consuming over two million tonnes of charcoal annually [1]. This dependence accelerates deforestation, land degradation, and greenhouse gas emissions, undermining sustainable energy transition goals [2]. National surveys and regional assessments consistently show that over two-thirds of Tanzanians rely on biomass fuels, while access to modern energy sources such as LPG and electricity remains below 10 % [3]. The resulting pressure on forests and air quality necessitates affordable, locally available, and renewable clean cooking solutions such as optimized biomass briquettes.

Biomass briquettes are solid blocks created through the densification or compaction of carbonized or uncarbonized biomass to enhance energy content and density, easing transportation, handling, and storage [4]. Different biomass materials like rice husks, coconut shells, and palm kernel shells, have been investigated as feedstocks for briquetting upon mixed with binding materials such as clay, starch and molasses [5,6]. Several binders, such as starch, molasses, and clay, have been examined for their application in biomass briquetting and palletization [7]. The shape and density facilitate efficient combustion, whereby high-density briquettes exhibit slower and more uniform combustion, thereby prolonging burn duration [8,9]. Studies showed that briquettes demonstrate enhanced performance relative to charcoal in terms of calorific value, combustion efficiency, and mechanical durability, thus highlighting their viability as a sustainable substitute for traditional wood fuel for small companies and residential cooking, effectively tackling energy crises and environmental issues [4].

Tanzania has abundant biomass residues that remain underutilized. Rice mills in Mbeya, Morogoro, and Shinyanga generate thousands of tonnes of husks annually, much of which is burned or dumped [10]. Coconut shells from coastal regions and palm kernel shells from oil-processing plants also accumulate as waste. Harnessing these resources for briquette production can provide a sustainable fuel alternative, reduce waste disposal problems, and create local employment opportunities [11].

Briquette technology has been pushed in the country for more than 30 years by both public and private organizations, with the goal of provision of an alternative to wood-based fuels (traditional firewood and wood charcoal) which is an energy-efficient and environmentally friendly. However, widespread adoption has been limited by inconsistent quality, lack of standardization, and weak market awareness. The Tanzania Bureau of Standards recently introduced **TZS 3545:2024**, setting thresholds for ash (≤27 %), moisture (≤10 %), volatile matter (≤25 %), fixed carbon (≥44 %), and gross calorific value (≥4300 kcal $kg^{-1}$). Meeting these standards requires improved control of raw materials, blending ratios, and binder composition [12].

In Tanzania, most briquette producers rely on single biomass feedstocks without standardized or optimized blending ratios of biomass and binders [13]. This lack of awareness often leads to inconsistent briquette quality and inefficient utilization of abundant high-ash residues such as rice husks, which are frequently discarded or openly burned, contributing to environmental pollution. The optimal combination of carbonized biomass and binder type remains largely unexplored in local production, limiting the potential to enhance fuel properties and promote sustainable clean cooking solutions. This study addresses these gaps by systematically optimizing blends of multiple carbonized residues including rice husks, coconut shells, and palm kernel shells with different binders (starch, molasses, clay) at varying ratios to improve energy content, reduce ash, and increase mechanical durability. By valorizing low-grade biomass through scientifically guided formulation, the research aims to provide practical guidelines for producers and support cleaner, more efficient briquette production in Tanzania and comparable African contexts.

## Materials and methods

### *Feedstock collection and preparation*

Biomass feedstocks including coconut shells, forest wastes (tree branches and top), palm kernels, and rice husks, were collected from local processing industries in the Coastal, Morogoro, and Mbeya regions of Tanzania. Each feedstock was air-dried to achieve a moisture content of 12 % – 8 % and then carbonized in a locally fabricated eco-friendly kiln (Carbonizer) (see Supplementary Fig. S1) at 400–500 °C under limited oxygen for 6 h. The carbonized materials were then cooled, crushed, and sieved through a 2 mm mesh to obtain a uniform particle size suitable for briquetting. The resulting biochar were stored in airtight containers to prevent moisture absorption prior to blending and binder addition.

### *Binding material preparation*

Three types of binder (starch, molasses, and clay) were chosen based on their availability, cost, and adhesive properties. A starch paste was prepared by dissolving cassava starch (10 wt %) in boiling water while continuously stirring until gelatinization was achieved. Molasses binder was diluted with warm water in a 3:1 wt ratio, while clay binder was combined with water to create a slurry. The binders were incorporated into the biochar feedstocks at concentrations of 20 %, 25 %, and 30 % (w/w) to assess their impact on fuel quality and briquette strength.

### *Designing and briquetting process*

The study involved two types of briquette formulations: one using individual biochar (coconut shell, palm kernel shell, charcoal dust, or rice husk) (see Supplementary Table S1); and another using blends where rice husk was mixed with other biochar (coconut shell, palm kernel shell, and charcoal dust) in different proportions (see Supplementary Table S2). For the single-biochar system, starch, clay, and molasses were used as binders at ratios of 70:30, 75:25, and 80:20 (biochar: binder, wt %). In the blended system, only starch binder was applied at different ratios, where lastly formulation of 75:25 was selected for blending system. All the prepared mixtures were homogenized at a controlled moisture of 20–25 %, then compacted into oval shape mold of a roller press at 150 psi. The molded briquettes were air-dried for 48 h and then oven-dried at 105 °C for 4 h to achieve stable moisture content below 10 % [14]. The process flow of biomass briquette production using carbonized forest and agricultural wastes (see Supplementary Fig. S2).

### *Proximate and energy parameters analysis*

Proximate and energy analysis were conducted according to American Society for Testing and Materials (ASTM), to determine the moisture content, ash content, volatile matter, fixed carbon, and gross calorific values, of the produced briquette samples [15,16]. Each analysis was performed in triplicate, and mean values were reported. In addition, the results were evaluated against the Tanzania National Standard for household solid biofuels (TZS 3545:2024), which specifies the following limits for briquettes: Ash ≤ 27 %, Moisture ≤ 10 %, Volatile matter ≤ 25 %, Fixed carbon ≥ 44 %, and Gross Calorific Value (GCV) ≥ 4300 kcal/kg. This standard is derived from ISO 17225–1:2021 to suit Tanzania household energy applications. The proximate parameters were computed using the following expressions:

*Moisture content*

The moisture content indicates the quantity of water in the sample, which directly influences its combustion efficiency and storage stability [17]. The moisture content was determined in accordance with ASTM D3173 using Eq. (1) [16].

$$M_c = \left(\frac{W_2 - W_3}{W_2 - W_1}\right) \times 100\% \tag{1}$$

Where, $M_c$ is Moisture Content (wt %), $W_1$ is weight of empty crucible (g), $W_2$ is weight of original sample and crucible before heating (g), $W_3$ is weight of sample and crucible after heating (g).

*Volatile matter*

Volatile matter is defined as the components of biomass that are emitted as gases after heating, excluding moisture. The assessment of volatile matter was conducted following ASTM Test No D3176, through Eq. (2) [16].

$$V_m = \left[\left(\frac{W_2 - W_3}{W_2 - W_1}\right) \times 100\%\right] - M_c \tag{2}$$

In this context, $V_m$ represents volatile matter (wt %), $M_c$ denotes the moisture content of the same sample (wt %), $W_1$ indicates the mass of the empty crucible (g), $W_2$ refers to the mass of the original sample along with the crucible prior to heating (g), and $W_3$ mass of the sample and crucible subsequent to heating (g).

*Ash content*

Ash content is the inorganic mineral residue that remains after full burning, lowering the fuel quality and calorific value of the materials [18]. It was assessed in accordance with ASTM D1102 for the determination of Ash Content [16]. It was determined using Eq (3):

$$A_c = \left(\frac{W_3 - W_1}{W_2 - W_1}\right) \times 100\% \tag{3}$$

where; $A_c$ is Ash Content (wt %), $W_1$ is weight of empty crucible (g), $W_2$ is weight of original sample and crucible before heating (g), $W_3$ is weight of sample and crucible after heating (g).

*Fixed carbon*

Fixed carbon represents the solid combustible residue that remains following the release of volatile matter, significantly affecting the combustion rate and thermal output [19]. It was determined by difference according to ASTM D3172 using Eq. (4).

$$F_c = 100 - (M_c + V_m + A_c) \tag{4}$$

where; $F_C$ is Fixed Carbon (wt %), $V_m$ is Volatile Matter (wt %), $M_c$ is Moisture Content (wt %), and $A_c$ is Ash Content (wt %).

*Gross calorific value*

Gross calorific value (GCV) represents the total heat energy released from complete combustion of the biomass sample [15]. It was determined using an Oxygen Bomb Calorimeter (Model 6400) following ASTM D5865.

Optimal formulations were identified based on the highest calorific value, lowest ash content, and superior mechanical stability.

*Mechanical and combustion characteristics*

The performance of biomass briquettes is determined by both their energy content and their physical durability and combustion characteristics. A series of mechanical and combustion tests were conducted to evaluate these aspects, concentrating on parameters that represent real-world handling, storage, and combustion conditions. Factors include shatter resistance (ASTM D440–86), which evaluates mechanical strength; water resistance, indicating moisture tolerance; ignition time, reflecting usability; and burning rate, representing combustion efficiency were determined in accordance with standardized procedures and pertinent literatures.

*Shatter resistance*

Shatter resistance denotes the mechanical and durability of briquettes, signifying their capacity to endure handling, transportation, and storage without substantial fracture. It was assessed in accordance with ASTM D440–86 (2002) by calculating the weight % of fines or fragments in relation to the initial weight of the briquettes as described in Eqs. (8) and (9) below.

$$\%W_l = \left(\frac{W_1 - W_2}{W_1}\right) \times 100 \tag{8}$$

$$SR = 100 \ - \%W_l \tag{9}$$

where, $W_l$ is Weight loss (wt %), $W_1$ is initial weight of briquette before dropping, $W_2$ is weight of briquette retained after dropping and SR is Shutter resistance.

*Water resistance*

Water resistance quantifies the ability of material (briquette) to resist moisture absorption during storage or utilization, directly affecting their combustion efficiency and longevity. The water resistance was determined using Eqs (10) and (11).

$$W_g = \left[\frac{W_2 - W_1}{W_2}\right] \times 100\% \tag{10}$$

$$WR = 100\% - W_g \tag{11}$$

where, $W_g$ is water gained (wt %) by briquette, $W_1$ is initial weight of briquette before immersion, $W_2$ is final weight of briquette after immersion.

*Ignition time*

Ignition time denotes the duration required for a briquette to ignite, indicating its usability and appropriateness as a domestic or industrial fuel. It was measured from the moment the burner was ignited until the initial observable combustion of the briquette, as specified in Eq (12).

$$Ignition\ time = t_1 - t_2 \tag{12}$$

where, $t_1$ is the time the briquette ignited (min), $t_0$ = time the burner was lit (min).

*Burning rate*

Burning rate is the rate at which fuel mass is consumed during combustion, indicating the efficiency and heat release profile of briquettes. It was determined from the weight loss per unit time using Eq. (13) below:

$$B_r = \frac{W_1 - W_2}{t} \tag{13}$$

where $W_1$ is the weight of fuel before burning completely (g), $W_2$ is the weight of fuel after burning completely (g), t is the total time taken for fuel to burn completely.

The combined evaluation of feedstock and binder types represents a novel optimization framework designed to upgrade high-ash residues like rice husk and to develop a standardized approach for sustainable biomass fuel production under Tanzanian conditions.

## Results and discussion

### *Effect of feedstock type on briquette properties*

The proximate and energy properties of the raw feedstocks used for briquette production are summarized in Table 1.

The proximate analysis indicated notable differences in composition among the carbonized feedstocks (Table 1). Coconut shell, palm kernel shell, and charcoal dust demonstrated elevated fixed carbon levels exceeding 65 % and low ash content below 10 %. In contrast, rice husk displayed a high ash content surpassing 40 % and a low carbon yield. This difference is attributable to the inherent mineral composition of the raw materials, as silica-rich rice husk produces significant ash during combustion. The results in Table 2, showed that the all briquettes complied with the standard limits for moisture content ($\leq$10 %) and volatile matter ($\leq$25 %). However, briquette produced from coconut shell, charcoal dust, and palm kernel shell, exhibited low ash content and significant calorific values ranging from 4372 to 6737 kcal/kg (Fig. 1), (see Supplementary Figs. S3 – S4) thereby complying with Tanzanian and ISO standards for household solid biofuels.

The findings substantiate earlier research indicating that elevated lignin and carbon content in coconut shell and palm kernel shell enhances briquette energy density and combustion efficiency . Similarly, Yirijor et al. [20] and Nonsawang et al. [21] reported improved energy and mechanical characteristics demonstrated similar results consistent with the present results. In contrast, produced briquettes from rice husk exhibited the high ash content (38–52 %) and low fixed carbon (<44 %), resulting in suboptimal calorific values (2441–3859 kcal/kg), and weak structural integrity (see Supplementary Figs. S5 and S9).

The results generally confirm that feedstock type is a key factor briquette energy density and mechanical performance. Materials exhibiting elevated fixed carbon content and reduced ash levels demonstrate enhanced combustion efficiency and durability, reflected by shorter ignition times and steadier burning (see Supplementary Figs. S6 – S8) compared to rice husk briquettes, which burned slowly and irregularly due to their high silica content.

### *Influence of binder type and ratio on briquette*

The choice of binder had a substantial impact on the structure, stability, and calorific value of the briquettes [22]. Of the three binders evaluated, starch demonstrated superior performance, resulting in briquettes (made from coconut shell, palm kernel shell and charcoal dust) with reduced ash content (Fig. 1), and (see Supplementary Figs. S3-S4), enhanced shatter resistance (>93 %), and improved combustion efficiency (see Supplementary Figs. S6-S8) [23]. The briquettes containing 20 % starch exhibited the optimal balance of strength and energy output, indicating that an excess (25 % and 30 %) of binder does not necessarily improve performance and may instead lead to increased ash content and reduced carbon density. The use of cassava starch binder promotes stronger particle bonding and enhanced material cohesion [24], leading to higher shatter index values that reflect superior briquette quality and durability. Hence, the briquettes produced in this study are mechanically robust and suitable for handling, storage, and transportation.

Molasses-based briquettes exhibited moderate strength, accompanied by a slightly elevated ash content attributed to residual minerals and incomplete carbonization [25]. The use of clay binder enhances shape retention but results in an increased ash content of

**Table 1**
Preliminary analysis results of carbonized biomass raw materials.

| Material Type | ASH ( %) | M ( %) | VM ( %) | FC ( %) | GCV (Kcal/Kg) |
|---|---|---|---|---|---|
| Coconut shell | 2.0 | 5.3 | 18.0 | 79.0 | 7387 |
| Rice husk | 41.5 | 5.3 | 10.0 | 43.2 | 3935 |
| Charcoal dusts | 1.7 | 6.1 | 26.0 | 61 | 6102 |
| Pam kernel shell | 8.5 | 2.3 | 23.0 | 66.0 | 6428 |

**Table 2**
Analysis of carbonized biomass briquette produced from individual biomass materials.

| Biochar | Biochar: Binder Ratio | Sample ID | Binder | ASH ( %) | M ( %) | VM ( %) | FC ( %) | GCV (Kcal/ Kg) | BR (g/ min) | WR ( %) | SR ( %) | **IT (min)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Charcoal Dusts** | 80:20 | CHS80 | Starch | 7 | 5 | 17 | 71 | 6615 | 5 | 96 | 99 | 4 |
| | 75:25 | CHS75 | Starch | 8 | 6 | 18 | 68 | 6353 | 4 | 94 | 98 | 4 |
| | 70:30 | CHC70 | Clay | 26 | 9 | 19 | 46 | 4543 | 3 | 87 | 96 | 7 |
| | 75:25 | CHC75 | Clay | 25 | 9 | 21 | 44 | 4451 | 4 | 88 | 95 | 6 |
| | 80:20 | CHM80 | Molasses | 8 | 8 | 19 | 65 | 6181 | 6 | 91 | 97 | 4 |
| | 75:25 | CHM75 | Molasses | 9 | 7 | 21 | 63 | 6085 | 7 | 91 | 98 | 4 |
| **Coconut shell** | 80;20 | CS80 | Starch | 2 | 9 | 17 | 72 | 6737 | 8 | 95 | 99 | 3 |
| | 75:25 | CS75 | Starch | 6 | 6 | 23 | 65 | 6299 | 7 | 94 | 99 | 2.5 |
| | 70:30 | CC70 | Clay | 27 | 10 | 19 | 44 | 4372 | 6 | 87 | 97 | 5 |
| | 75:25 | CC75 | Clay | 26 | 9 | 18 | 47 | 4590 | 5 | 88 | 96 | 4 |
| | 80:20 | CM80 | Molasses | 7 | 7 | 21 | 65 | 6257 | 8 | 92 | 98 | 2.5 |
| | 75:25 | CM75 | Molasses | 8 | 6 | 23 | 63 | 6161 | 9 | 91 | 99 | 2 |
| **Palm kernel shells** | 80:20 | PS80 | Starch | 9 | 7 | 17 | 67 | 6299 | 7 | 94 | 99 | 3.5 |
| | 75:25 | PS75 | Starch | 10 | 8 | 18 | 64 | 6056 | 6 | 93 | 98 | 3 |
| | 70:30 | PC70 | Clay | 27 | 7 | 20 | 46 | 4579 | 5 | 88 | 96 | 5.5 |
| | 75:25 | PC75 | Clay | 26 | 5 | 22 | 47 | 4739 | 4 | 86 | 95 | 4.5 |
| | 80:20 | PM80 | Molasses | 9 | 7 | 21 | 63 | 6085 | 7 | 90 | 97 | 3 |
| | 75:25 | PM75 | Molasses | 8 | 5 | 24 | 63 | 6198 | 8 | 90 | 98 | 2.5 |
| **Rice husks** | 80:20 | RS80 | Starch | 41 | 4 | 15 | 40 | 3859 | 4 | 64 | 77 | 7.5 |
| | 75:25 | RS75 | Starch | 39 | 7 | 21 | 34 | 3536 | 3 | 62 | 75 | 6.5 |
| | 70:30 | RC70 | Clay | 52 | 6 | 21 | 21 | 2441 | 2 | 54 | 63 | 9 |
| | 75:25 | RC75 | Clay | 47 | 7 | 21 | 26 | 2846 | 3 | 56 | 61 | 8 |
| | 80:20 | RM80 | Molasses | 40 | 7 | 16 | 37 | 3654 | 5 | 58 | 67 | 6.5 |
| | 75:25 | RM75 | Molasses | 38 | 8 | 16 | 38 | 3742 | 6 | 59 | 65 | 5.5 |
| **Standard** | | | | **≤27** | **≤10** | **≤25** | **≥44** | **≥4300** | **≤10** | **≥80** | **≥80** | **≤10** |

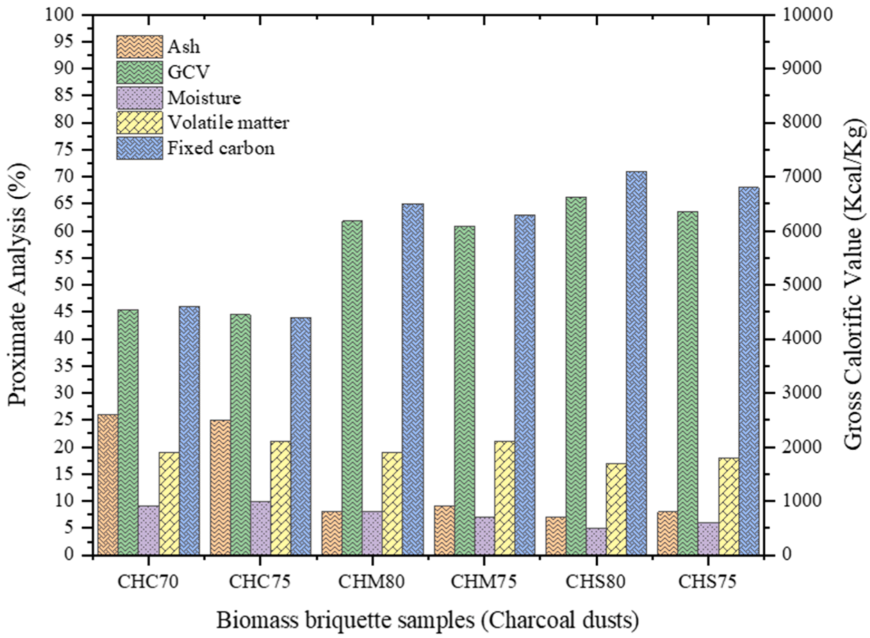


**Fig. 1.** Proximate analysis and heat value for biomass briquettes made by carbonized forest wastes.

up to 14 % and a nearly 10 % reduction in calorific value ranging from 2441 to 2846 kcal/kg for made from rice husks (see Supplementary Fig. S8) and 4372 to 4739 kcal/kg for briquettes of coconut shell, palm kernel shell and charcoal dust (see Supplementary Figs. S3 – S5). This is due to its non-combustible nature [26]. Consequently, clay should be utilized carefully or in conjunction with organic binders to ensure satisfactory energy performance.

The combustion properties further reinforced the impact of binder type on fuel quality. Briquettes bonded with starch exhibited rapid ignition and sustained burning rates, demonstrating efficient heat release and consistent flame patterns. Molasses-bonded briquettes exhibited similar ignition characteristics but demonstrated a marginally accelerated burn rate attributable to residual sugars that facilitate volatile release. Clay-bonded briquettes exhibited extended ignition times and slower combustion rates, which correlate with their elevated ash content and diminished carbon reactivity [27,28]. Starch-bonded briquettes ignited more rapidly and combusted more uniformly than those bound with molasses or clay, demonstrating that the type of binder directly affects combustion efficiency, strength, and calorific value as shown by Achebe et al. [23] and Okegbile et al. [29].

*Optimization of blended briquettes*

The incorporation of high-energy feedstocks with rice husk significantly enhanced briquette performance (Table 3). The 60:40 ratio of biochar to rice husk enhanced the calorific value to 4741–5552 kcal/kg and decreased ash content to below 20 % (Fig. 2). Mechanical tests demonstrated improved shatter resistance (>92 %) and water stability, indicating robust structural cohesion among the blended materials (Fig. 3). These results are consistent with Kpalo et al. [30], who obtained values between 98.3 % and 99.1 % for corncob and oil palm trunk bark briquettes.

Coconut shell–rice husk (CR40) and palm kernel shell–rice husk (PR40) briquettes demonstrated superior energy properties, whereas charcoal dust–rice husk (CHR40) blends exhibited the highest mechanical durability. The enhanced performance can be attributed to the higher carbon concentration and cohesive bonding characteristics of the denser biochar, which effectively reduce the adverse effects of non-combustible (silica) from rice husk [31]. The 50:50 biochar-to-rice husk blend demonstrated a decrease in performance, attributed to the increased ratio of rice husk compared to the optimized 60:40 system [32]. Despite this ratio (50:50), the briquettes exhibited adequate fuel properties, making them appropriate for domestic and small-scale commercial use. In addition, the 60:40 blended briquettes exhibited balanced combustion behavior (Fig. 3) compared with 50:50, with moderate ignition times and sustained burning rates, confirming their suitability for domestic applications.

The optimized formulations meet essential quality criteria of national and ISO standards, indicating that suitable blending can convert low-grade residues (rice husks) into usable cooking fuels. This result has significant practical implications for Tanzania, where the disposal of rice husks continues to pose an environmental challenge. The wide availability and low cost of rice husk justify efforts to enhance its fuel quality through strategic blending and binder optimization.

*Environmental and socioeconomic relevance*

The optimized briquettes offer key environmental and socioeconomic advantages for Tanzania's energy transition. Charcoal production significantly contributes to forest depletion, resulting in an estimated annual loss of 470,000 hectares of woodland between 2012 and 2021 [33]. Replacing over one million tonnes of urban charcoal demand annually, equivalent to 109,500 ha of forest loss, with biomass briquettes could conserve about 1.2 million tonnes of wood each year [34]. Studies indicate that briquetting with carbonization significantly lowers greenhouse gas emissions, with findings revealing a >70 % reduction in greenhouse gas emissions and a 49–74 % decrease in pollutants such as carbon monoxide (CO), methane ($CH_4$), and particulate matter (PM2.5) when compared to conventional burning methods [35].

Agricultural residues, including coconut shells, palm kernel shells, and rice husks, are readily accessible at low cost within the community context. The research showed that utilization such materials for briquette production can create rural employment (collection and selling biomass raw materials), facilitate waste valorization, and decrease open burning practices that release particulate matter and methane [36,37]. This method converts waste into energy, thereby aligning with the principles of a circular economy and national climate goals.

The proposed technology aligns with Tanzania's National Clean Cooking Strategy (2024–2034), which aims for an 80 % adoption rate of clean cooking solutions by 2034 [38]. The production of briquettes from locally sourced biomass residues facilitates the transition to cleaner energy by providing an economical, renewable, and carbon-neutral alternative to charcoal. This process is consistent with Tanzania's Nationally Determined Contributions (NDCs) as outlined in the Paris Agreement, aimed at decreasing greenhouse gas emissions within the energy sector. The eco-friendly carbonizer (kiln) employed in this study (see Supplementary Fig. S1) enhances environmental performance by recycling emitted syngas components (Carbon monoxide (CO), Methane ($CH_4$), and Hydroen ($H_2$)) back into the combustion chamber to sustain the carbonization, thereby reducing waste and dependence on external energy sources. Moreover, the system yields pyrolysis oil (wood vinegar or wood acid) as valuable by-product, which can serve as an industrial feedstock for fertilizer production and as a flavoring or browning agent in food processing.

**Table 3**
Analysis of carbonized biomass briquette produced from blends of biomass materials.

| Sample ID | Biochar & Binder Ratio | Biochar Ratio | ASH (%) | M (%) | VM (%) | FC (%) | GCV (Kcal/Kg) | BR (g/min) | WR (%) | SR (%) | IT (min) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CHR40 | 75:25 | 60:40 | 19 | 7 | 14 | 60 | 5552 | 5 | 94 | 99 | 4 |
| CR40 | 75:25 | | 20 | 7 | 18 | 55 | 5277 | 5 | 95 | 98 | 5 |
| PR40 | 75:25 | | 25 | 6 | 22 | 47 | 4741 | 6 | 93 | 99 | 4 |
| CHR50 | 75:25 | 50:50 | 28 | 8 | 20 | 44 | 4408 | 3 | 91 | 93 | 8 |
| CR50 | 75:25 | | 30 | 7 | 22 | 41 | 4225 | 3.5 | 89 | 91 | 7 |
| PR50 | 75:25 | | 33 | 6 | 22 | 39 | 4051 | 4 | 87 | 89 | 6 |
| **Standard** | | | **≤27** | **≤10** | **≤25** | **≥44** | **≥4300** | **≤10** | **≥80** | **≥80** | **≤10** |

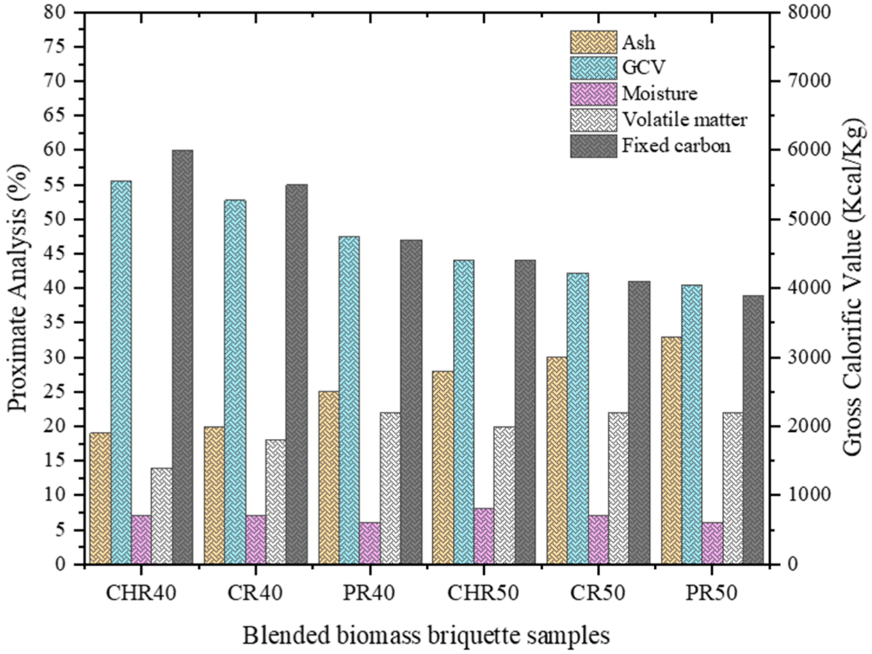


**Fig. 2.** Proximate analysis and heat value for biomass briquettes made by a blend of charcoal, coconut and palm kernel shell with carbonized rice husks.

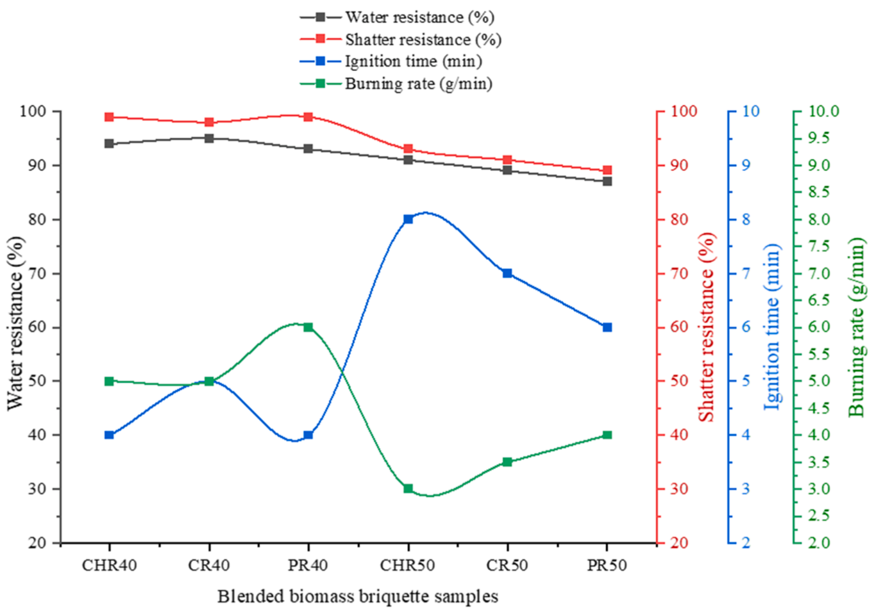


**Fig. 3.** Mechanical and combustion tests for biomass briquettes made by a blend of charcoal, coconut, and palm kernel shell with carbonized rice husks.

*Alignment of policy and sustainable development goals*

The findings have significant implications for Tanzania's sustainable development objectives. This study offers an evidence-based framework for optimizing biomass briquettes, thereby contributing to several United Nations Sustainable Development Goals (SDGs) [39]: This initiative specifically supports SDG 7 (Affordable and Clean Energy, Target 7.1) by facilitating access to affordable, reliable, and modern cooking energy sourced from renewable biomass resources. This also supports SDG 12 (Responsible Consumption and Production, Target 12.2) by promoting the efficient use of agricultural residues and minimizing the environmental impacts linked to waste disposal. The integration of optimized briquetting technologies supports SDG 13 (Climate Action, Target 13.2) by promoting climate-resilient energy systems that reduce greenhouse gas emissions and enhance Tanzania's climate change response.

In addition, the work supports the African Union's Agenda 2063 Goal 7, which focuses on environmentally sustainable and climate-resilient economies at the continental level [40]. The optimized briquetting framework serves as a model for clean energy entrepreneurship that can be adapted throughout Africa, especially in areas with comparable agricultural residue availability.

## Conclusion

This study demonstrated that optimizing feedstock composition and binder ratio markedly improves the energy, combustion, and mechanical performance of biomass briquettes. Coconut shell, palm kernel shell, and charcoal dust produced high-quality briquettes with calorific values above 6200 kcal/kg, low ash (<10 %), and high fixed carbon (>65 %). In contrast, rice husk alone yielded substandard briquettes due to its high silica content. Blending rice husk with high-energy biochar at a 60:40 ratio enhanced calorific value (4741–5552 kcal/kg), reduced ash content (<20 %), and improved shatter resistance (>92 %) and water stability. The 50:50 blend exhibited moderate performance, with higher ash and longer ignition times, indicating that 60:40 is the optimal formulation for balanced combustion and durability. Among the binders tested, starch produced the best overall results, yielding briquettes with high shatter resistance (>93 %), rapid ignition (2–4 min), and steady burning rates (4–8 g $min^{-1}$). Molasses-based briquettes exhibited moderate strength and acceptable energy output but slightly higher ash content due to residual minerals, while clay binders improved shape retention yet lowered calorific value and prolonged ignition due to their non-combustible nature. The optimal starch loading was 20 % for single-feedstock briquettes and 25 % for blended systems. Although optimized under laboratory conditions, future research should focus on field-based performance, economic feasibility, and the use of catalytic additives to further enhance combustion efficiency and long-term sustainability.

## CRediT authorship contribution statement

**Kevin Nsolloh Lichinga**: Conceptualization, Methodology, Writing – original draft, Software, Investigation, Data curation. **Kunda Sikazwe**: Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Data curation, Funding acquisition. **Rahel Elibariki**: Conceptualization, Methodology, Writing – review & editing, Supervision, Data curation, Project administration, Funding acquisition. **Augustino Alfred Masse**: Methodology, Writing – review & editing, Data curation, validation. **Hossen Iddi Kayumba**: Methodology, Writing – review & editing, Data curation, validation. **Hubert Shija**: Writing – review & editing, Resources, Supervision, Validation, Project administration, Funding acquisition.

## Data availability

Data will be made available on request.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sciaf.2025.e03056.

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