
ENGINEERING SUSTAINABLE SOLID BIOFUELS FOR NIGERIA'S CLEAN ENERGY TRANSITION: COMPARATIVE PERFORMANCE EVALUATION OF INDIVIDUAL AND BLENDED AGRO-RESIDUE BRIQUETTES

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ABSTRACT

Nigeria's transition toward a sustainable, low-carbon energy system necessitates decentralized engineering solutions capable of converting abundant agricultural residues into clean, high-performance solid biofuels. This study presents a comparative experimental evaluation of solid biofuels engineered from maize straw, rice straw, wheat straw, and selected binary blends, characterized across 18 distinct formulations using cassava starch, Gum Arabic, and coal tar as binders under compaction pressures of 5 and 10 MPa. Characterization included higher heating value (HHV), ash content, moisture content, compressive strength, ignition time, burning rate, and water resistance index (WRI). Two-way Analysis of Variance (ANOVA) and Pearson correlation analyses demonstrated that biomass composition is the primary determinant of thermal behavior and ash characteristics. The 50:50 maize–wheat straw blend bonded with coal tar at 5 MPa (5M5Wc5) recorded the highest HHV (20.5 MJ kg⁻¹), the shortest ignition time (10 s), and a relatively low ash content (7.0%). The highest compressive strength was recorded by the Gum Arabic-bonded wheat straw formulation Wg5 (206.9 kN m⁻²). Across the full dataset, ash content was negatively associated with HHV ($r = -0.696$), whereas the correlation between compressive strength and WRI is also negative at $r = -0.29$. In Phase II, exploratory two-way ANOVA without replication indicated a statistically significant main effect of compaction pressure on moisture content ($p = 0.0017$), but not on compressive strength ($p = 0.6175$); interaction effects could not be independently estimated. The results demonstrate application-specific trade-offs among thermal performance, mechanical integrity, moisture resistance, and environmental considerations. By converting agricultural residues into value-added solid fuels, the study supports resource recovery and circular-bioeconomy pathways while providing an engineering basis for decentralized biomass-energy systems in Nigeria.

Keywords: Biomass densification; Binder characteristics; Rice straw; Wheat straw; Maize straw; Waste Valorization; Circular Bioeconomy

1. INTRODUCTION

The global transition towards low-carbon energy systems has accelerated efforts to diversify renewable energy portfolios, improve energy security, and reduce greenhouse gas emissions in line with the Paris Agreement and the United Nations Sustainable Development Goals (SDGs). Sustainable bioenergy remains a critical component of the global energy transition because it provides dispatchable renewable energy, supports waste valorization, and contributes to decarbonizing sectors that are difficult to electrify, such as hard-to-electrify thermal applications. Modern bioenergy applications are increasingly viewed as complementary to solar and wind power within integrated renewable energy systems (IPCC, 2022).

Nigeria's growing population, rapid industrialization, and increasing demand for reliable, affordable, and sustainable energy have intensified the need for engineering solutions that address energy security, economic development, and climate change mitigation. Despite abundant renewable energy resources, energy poverty remains a major national challenge, motivating the development of innovative technologies that support both universal energy access and long-term decarbonization (International Energy Agency [IEA], 2025; Nigeria Energy Transition Plan [NETP], 2022). The Nigeria Energy Transition Plan establishes a national pathway towards net-zero emissions by 2060

while prioritizing energy access, clean cooking, industrial development, and renewable energy diversification (Nigeria Energy Transition Plan [NETP], 2022).

Within the cooking sector, the ETP identifies the transition away from traditional firewood and charcoal towards cleaner fuels—including modern biofuels, biogas, electricity, and other low-carbon cooking technologies—as a critical strategy for achieving Sustainable Development Goal 7 while reducing emissions and improving public health. The plan also recognizes the importance of developing local biofuel markets and supporting research and innovation for biomass conversion technologies, particularly in rural communities where biomass resources are abundant. Consequently, engineering innovations that convert agricultural residues into high-quality solid biofuels are increasingly recognized as essential components of sustainable energy systems, promoting resource efficiency, waste valorization, and circular bioeconomy strategies (Mujtaba et al. (2023); Sadh, et al., (2023)).

1.1 Engineering Variables Governing Biomass Briquette Performance

Among the various biomass conversion technologies, densification through briquetting has emerged as one of the most practical engineering solutions for upgrading low-density loose agricultural residues into high-quality uniform solid biofuels suitable for domestic, commercial, and industrial thermal applications. Briquetting substantially reduces volume, increases bulk density, and improves storage stability, handling characteristics, and transportation efficiency. It also improves fuel uniformity, enhances combustion characteristics, and produces fuels with improved mechanical integrity and more consistent energy performance (Grover & Mishra, 1996; Kaliyan & Morey, 2009; Tumuluru et al., 2011), with a potential for partially replacing traditional fuels such as firewood, charcoal, and coal in decentralized energy systems.

The quality of briquettes is governed by several interacting variables, including feedstock characteristics, particle size, moisture content, binder type and concentration, compaction pressure, and post-production drying conditions. These parameters influence important fuel quality indices such as calorific value, ash content, compressive strength, ignition behaviour, burning characteristics, and resistance to moisture (Tumuluru et al., 2011; Zhang et al., 2018). Agricultural residues differ considerably in their composition, ash-forming minerals, and natural binding characteristics; consequently, combining different feedstocks offers opportunities to exploit complementary material properties while minimizing the limitations associated with individual biomass resources. Likewise, binder selection determines the strength and durability of briquettes, whereas compaction pressure governs particle rearrangement, contact area, mechanical interlocking, and final briquette density (Sikarwar et al., 2016; Tumuluru et al., 2011).

1.2 Current Knowledge Gaps and Objectives

Although considerable progress has been made in biomass briquetting technology, existing studies have predominantly focused on individual agricultural residues, single binder systems, or isolated processing variables. Many investigations evaluate only one aspect of briquette production, such as calorific value, mechanical strength, or combustion performance, making direct comparison among studies difficult (Obi et al, 2022). Furthermore, relatively few studies (Walozi, et al, 2026) that systematically evaluated multi-variable interactions across multiple distinct processing phases within a single, harmonized experimental framework remains highly limited (Grover & Mishra, 1996; Kaliyan & Morey, 2009; Obi et al., 2022).

This study addresses these gaps by evaluating multiple biomass residues (maize straw, rice straw, wheat straw), several binder systems (cassava starch, Gum Arabic, coal tar), and different compaction pressures (5 and 10 MPa) within a harmonized experimental framework. By integrating these physical, thermal, mechanical, and combustion performance indicators within a single comparative framework, the study identifies the influence of biomass composition, binder characteristics, and densification conditions on briquette quality, providing practical recommendations for sustainable thermal energy production from agro-residues in Nigeria.

2. MATERIALS AND METHODS

The agro-residues investigated as feedstocks in this study comprised maize straw, rice straw, and wheat straw, selected because of their abundance as agricultural residues and their significant potential for renewable solid biofuel production. The residues were collected from agricultural farms around Samaru Zaria, and were cleaned manually to remove soil particles, stones, and other foreign materials. The cleaned residues were air-dried under ambient conditions to reduce their moisture content. The dried residues were chopped into smaller pieces and milled to obtain a relatively uniform particle size suitable for densification. The pulverized materials were sieved using a 2 mm mesh to ensure particle size uniformity and to minimize variability during compaction. The processed biomass materials were stored in airtight containers before briquette production to minimize moisture uptake from the environment. The overall process flow of feedstock preparation, briquetting, and characterization is shown in Figure 1.

2.1 Binder Preparation

Three binder materials with different binding characteristics were investigated, namely cassava starch, Gum Arabic, and coal tar. Cassava starch and Gum Arabic were selected as natural binders because of their availability and established adhesive properties (Ezechiel, 2022), whereas coal tar was included as a conventional binder for comparison of mechanical and combustion performance. The binders were prepared as follows (Plate 1):

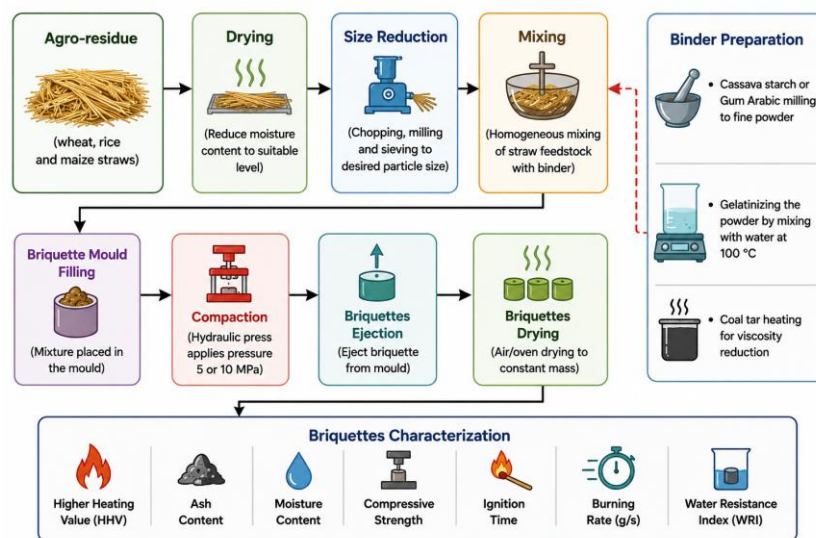


Figure 1: Block Flow Diagram of the Study

1. Cassava Starch Binder: Prepared by dispersing starch powder in water followed by heating with continuous stirring until gelatinization occurred at a temperature of 100 °C, producing a homogeneous adhesive paste. This temperature disrupts the intermolecular bonds, creating hydrogen-bonding networks. After cooking, the binder was allowed to cool for 45 minutes before use.
2. Gum Arabic Binder: Prepared by dissolving small quantities at a time in water that was boiled to 100 °C and allowed to cool to approximately 90 °C to obtain a uniform adhesive solution.
3. Coal Tar Binder: Heated to reduce its viscosity and then allowed to cool to ambient conditions before mixing directly as a binder.



Plate 1: (a) Cassava Starch (b) Starch binder (c) Prepared agro-residues (d) lubricant (oil)



Plate 2: (a) Cylindrical Steel Mould (b) Briquettes (Densified biomass)

2.2 Experimental Design Matrix

A comparative experimental approach was adopted to evaluate the effects of biomass composition, binder characteristics, and compaction pressure on briquette fuel quality. The investigation consisted of two complementary experimental phases as detailed in Table 1.

Table 1: Experimental Design Matrix

S/N	Phase	Sample Code	Feedstock Composition	Blend Ratio (% w/w)	Binder Type	Compaction Pressure (MPa)
1	I	Mg5	Maize straw	100:0	Gum Arabic	5
2	I	Mc5	Maize straw	100:0	Coal tar	5
3	I	Ms5	Maize straw	100:0	Starch	5
4	I	Wg5	Wheat straw	100:0	Gum Arabic	5
5	I	Wc5	Wheat straw	100:0	Coal tar	5
6	I	Ws5	Wheat straw	100:0	Starch	5
7	I	5M5Wg5	Maize straw + Wheat straw	50:50	Gum Arabic	5
8	I	5M5Wc5	Maize straw + Wheat straw	50:50	Coal tar	5
9	I	5M5Ws5	Maize straw + Wheat straw	50:50	Starch	5
10	II	Rs5	Rice straw	100:0	Starch	5
11	II	5R5Ms5	Rice straw + Maize straw	50:50	Starch	5
12	II	7R3Ms5	Rice straw + Maize straw	70:30	Starch	5
13	II	3R7Ms5	Rice straw + Maize straw	30:70	Starch	5
14	II	Rs10	Rice straw	100:0	Starch	10
15	II	Ms10	Maize straw	100:0	Starch	10
16	II	5R5Ms10	Rice straw + Maize straw	50:50	Starch	10
17	II	7R3Ms10	Rice straw + Maize straw	70:30	Starch	10
18	II	3R7Ms10	Rice straw + Maize straw	30:70	Starch	10

In the first phase (I), briquettes were produced from maize straw (M), wheat straw (W), and a 50:50 maize–wheat (5M5W) blend using three binder materials (Gum Arabic, coal tar, and cassava starch) under a compaction pressure of 5 MPa.

In the second phase (II), the influence of biomass composition and compaction pressure was investigated using rice straw, maize straw, and their binary blends (50:50, 70:30, and 30:70 ratios) bonded with cassava starch under compaction pressures of 5 MPa and 10 MPa, resulting in 18 distinct formulations (S/N 1-18).

2.3 Characterization Methods

Measured quantities of the prepared biomass feedstocks were thoroughly mixed with the appropriate binder to obtain homogeneous mixtures (Figure 1). The mixtures were fed into a lubricated cylindrical steel mould and compacted using a hydraulic briquetting press operating at the designated pressure (5 or 10 MPa). The compacted briquettes were ejected and air-dried under ambient laboratory conditions until constant mass was attained. Properties of interest were determined in accordance with standard ASTM protocols where applicable (Table 2).

Table 2: Standard Methods Adopted for Characterization

Property	Adopted Procedure/ Method	Description	References
HHV	ASTM D5865/ D5865M -19	Gross calorific value determination using an adiabatic bomb calorimeter.	ASTM International (2019)
Ash Content	ASTM E1755 -24	Ash determination by complete combustion of oven-dried biomass at 575 ± 25 °C.	ASTM International (2024b)
Moisture Content	ASTM E871 -24	Moisture content determination of particulate biomass by oven drying to constant mass.	ASTM International (2024a)
Compressive Strength	Adapted compression test (UTM)	Maximum compressive load sustained before physical failure using a Universal Testing Machine.	Obi et al. (2022)
Ignition Time	Experimental combustion method	Elapsed time from application of flame until sustained ignition is established.	Obi et al. (2022)
Burning Rate	Experimental combustion method	Measured mass loss per unit time (g/s) during active combustion.	Olugbade et al. (2019); Obi et al. (2022)
WRI	Water immersion method	Time elapsed to complete structural dissolution upon immersion in water.	Obi et al. (2022)

2.4 Statistical Methodology

The experimental data were analysed using two-way ANOVA without replication to provide an exploratory assessment of main-factor effects. Because only one observation was available for each factor combination, interaction effects could not be independently estimated and may be confounded with the residual term. Consequently, the resulting p-values should be interpreted as exploratory evidence of main effects under an additive-model assumption. For Phase I, the additive model evaluated Biomass Feedstock (Maize, Wheat, 50:50 blend) and Binder Type (Gum Arabic, coal tar, cassava starch) under a constant pressure of 5 MPa. For Phase II, an unbalanced Two-Way ANOVA was applied using Type II Sum of Squares to rigorously evaluate Rice-Maize blend ratios and compaction pressures (5 MPa vs 10 MPa) without factor-ordering bias

Pearson correlation analysis was executed on the complete 18-sample dataset to determine linear relationship coefficients (r) between all physical, thermal, and mechanical properties. The statistical significance threshold was set at $\alpha = 0.05$.

3. RESULTS AND DISCUSSION

3.1 General Briquette Performance

The physical, thermal, and mechanical properties of the 18 formulations are summarized in Table 3. The results show that the Higher Heating Value (HHV) varied substantially, ranging from 14.1 to 20.5 MJ/kg, but is comparable to standard solid biofuels. The moisture contents however, ranged from 21.4% to 34.4%, which significantly exceed the commercial solid biofuel standard of <15%. This indicates that the passive post-production ambient air-drying alone is insufficient. According to the international standard ISO 17225-7:2021 (ISO, 2021), the maximum moisture content of $\leq 15\%$ is necessary for commercial graded non-woody briquettes, to prevent physical

degradation, mold growth, and ignition delay during storage (ISO, 2021; Obi et al., 2022). Under the high relative humidity (RH) conditions typical of the study location, Zaria (RH from 36%–46% in dry season, to 82%–88% during the wet season (Yusuf & Shuaib, 2012)), the rate of air-drying limits water removal from the briquettes produced, thus requiring active thermal interventions.

Engineering Drying Process Recommendations: To bring the engineered briquettes to the standard non-woody biofuels moisture content within the ISO-compliant threshold (<15%), a controlled thermal drying stage – like a convective kiln-drying system operating at 60 °C to 80 °C for 12 to 18 hours is proposed (Obi et al., 2022). Maintaining the drying temperature below 100 °C is critical, to avoid damaging the cassava starch binder, as higher temperatures initiate the thermal decomposition and depolymerization of the starch adhesive, which collapses the solid-bridge molecular networks and severely weakens dry compressive strength (Tumuluru et al., 2011; Obi et al., 2022). From an engineering perspective, this active thermal drying carries a substantial energy penalty, as convective air dryers typically consume between 2.4 and 4.5 MJ of thermal energy per kg of water evaporated (Đurđević et al., 2021; Tumuluru et al., 2011).

Table 3: General Characterization Results of Densified Biofuels

S/N	Sample ID	Binder	HHV (MJ/kg)	Ash Content (%)	Moisture Content (%)	Ignition Time (s)	Burning rate (g/s)	Compressive Strength (kN/m ²)	WRI (min)
1	Mg5	Gum Arabic	17.3	6.1	28.87	14.0	0.22	195.4	15.0
2	Mc5	Coal tar	19.3	5.2	29.99	12.0	0.17	146.6	2.0
3	Ms5	Starch	18.0	5.8	26.83	15.0	0.24	181.0	2.7
4	Wg5	Gum Arabic	15.7	10.3	31.99	15.0	0.20	206.9	10.0
5	Wc5	Coal tar	16.2	9.2	32.51	17.0	0.23	172.4	7.5
6	Ws5	Starch	15.9	9.7	30.57	20.0	0.27	192.5	5.0
7	5M5Wg5	Gum Arabic	18.2	7.9	29.30	13.0	0.21	201.1	6.0
8	5M5Wc5	Coal tar	20.5	7.0	28.07	10.0	0.15	189.7	6.0
9	5M5Ws5	Starch	19.5	7.6	26.17	15.0	0.25	169.5	3.3
10	Rs5	Starch	14.5	9.0	31.40	20.0	0.23	91.0	10.0
11	5R5Ms5	Starch	14.7	9.5	31.70	17.0	0.20	192.3	5.0
12	7R3Ms5	Starch	14.7	13.9	33.60	15.0	0.23	176.7	6.0
13	3R7Ms5	Starch	14.4	9.1	34.40	11.0	0.17	184.5	3.8
14	Rs10	Starch	14.1	8.6	21.40	14.0	0.27	153.3	15.0
15	Ms10	Starch	17.7	8.2	25.70	10.0	0.20	122.5	2.0
16	5R5Ms10	Starch	14.2	12.8	25.10	18.0	0.23	197.5	7.5
17	7R3Ms10	Starch	15.8	10.7	25.10	14.0	0.23	148.5	6.0
18	3R7Ms10	Starch	14.9	9.1	24.40	12.0	0.17	187.1	3.3

To preserve a positive net energy ratio for the process, waste heat recovered from industrial boiler exhausts or waste heat recovery from the hydraulic briquetting machinery. Alternatively, incorporating solar-assisted convective tunnel dryers operating at 36.5–65 °C for 24 to 36 hours offers a highly viable, low-cost, decentralized engineering solution (Đurđević et al., 2021; Guibunda et al., 2026; Tumuluru et al., 2011).

3.2 Influence of Biomass Composition on Fuel Properties

The primary feedstock composition exerted a dominant role across both experimental phases. The agro-residues have distinct ash profiles and cellular arrangements, dictating their energy density and mechanical interlocking limits. ANOVA tests were completed for all seven response variables, and their exact results are tabulated below in Table 4 and Table 5.

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COMPARATIVE PERFORMANCE EVALUATION OF INDIVIDUAL AND BLENDED AGRO-RESIDUE
BRIQUETTES

Table 4: Phase I ANOVA Table (Biomass Feedstock & Binder Type under 5 MPa)

Property	Factor Source	Sum of Sq. (SS)	Degrees of freedom (df)	F-Statistic	p-value	Significance
HHV (MJ/kg)	Feedstock	18.5960	2	37.2740	0.0026	Highly Significant (p < 0.01)
	Binder	3.8490	2	7.7150	0.0424	Significant (p < 0.05)
	Residual	0.9980	4	-	-	-
Ash Content (%)	Feedstock	24.4960	2	1574.714	< 0.0001	Extremely Significant (p < 0.001)
	Binder	1.4160	2	91.0000	0.0005	Extremely Significant (p < 0.001)
	Residual	0.0310	4	-	-	-
Moisture Content (%)	Feedstock	25.0610	2	27.3070	0.0047	Highly Significant (p < 0.01)
	Binder	10.2880	2	11.2110	0.0229	Significant (p < 0.05)
	Residual	1.8350	4	-	-	-
Ignition time (s)	Feedstock	36.2222	2	8.5790	0.0357	Significant (p < 0.05)
	Binder	21.5556	2	5.1053	0.0792	Marginally Significant
	Residual	-	-	-	-	-
Burning rate	Feedstock	0.0015	2	1.1261	0.4093	Not Significant
	Binder	0.0075	2	5.6639	0.0681	Marginally Significant
	Residual	-	-	-	-	-
Compressive Strength (kN/m ²)	Feedstock	433.8870	2	1.0360	0.4340	Not Significant
	Binder	1532.5270	2	3.6590	0.1249	Not Significant
	Residual	837.5870	4	-	-	-
WRI	Feedstock	8.7822	2	0.3451	0.7273	Not Significant
	Binder	73.3889	2	2.8838	0.1677	Not Significant
	Residual	-	-	-	-	-

Note: residual df = 4 for each property; residual terms are omitted for compactness. Interaction effects are not separately estimable in this unreplicated design

3.2.1 Thermal and Fuel Properties (Phase I ANOVA Evaluation)

The Phase I Two-Way ANOVA established that biomass feedstock selection is a statistically significant driver of HHV (p = 0.0026), Ash Content (p < 0.0001), and Moisture Content (p = 0.0047). Pure maize straw briquettes achieved lower ash contents (5.2%–6.1%) and higher heating values (17.3–19.3 MJ/kg) compared to pure wheat straw, which was penalized by elevated ash (9.2%–10.3%) and lower HHV (15.7–15.9 MJ/kg). Blending these residues in a 50:50 ratio (5M5W series) successfully moderated the high ash penalty of wheat straw (reducing ash to 7.0%–7.9%) while

preserving an attractive HHV (18.2–20.5 MJ/kg). This highlights biomass blending as a primary fuel optimization strategy.

3.2.2 Combustion characteristics (Phase I)

Feedstock selection exerted a significant effect on ignition time ($p = 0.0357$). Pure maize straw briquettes ignited more rapidly (avg. 13.7 s) than pure wheat straw briquettes (avg. 17.3 s). This difference is attributed to ash composition: the higher inorganic mineral fractions (such as silica) in wheat straw act as a thermal barrier during heating, absorbing heat without decomposing, which delays the temperature rise necessary for volatilization and ignition.

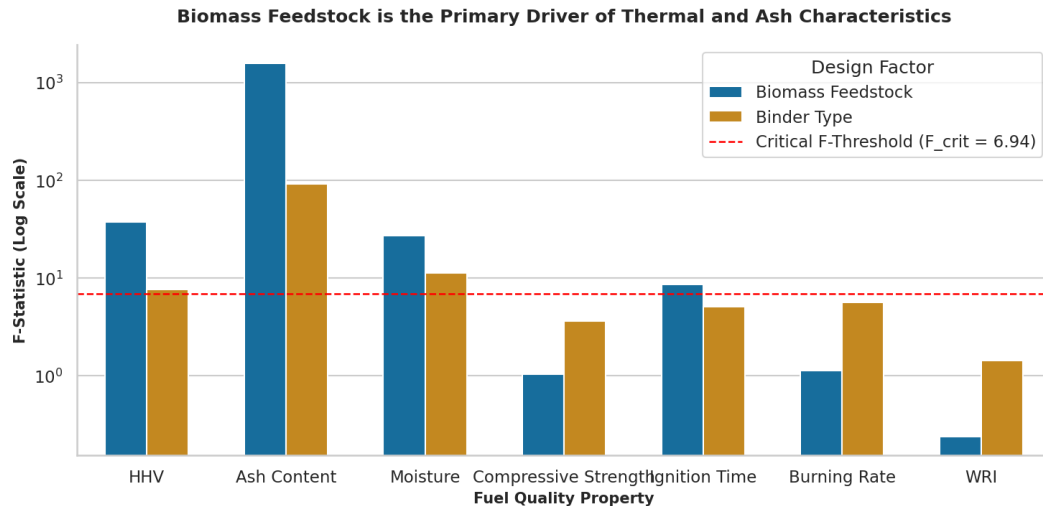


Figure 2: Phase I ANOVA F-statistics showing feedstock and binder type significance across properties relative to critical F-threshold (6.94).

3.3 Influence of Binder Characteristics on Biofuel Quality

Binder type significantly influenced HHV ($p = 0.0424$) and Ash Content ($p = 0.0005$). Natural binders (cassava starch and Gum Arabic) produced intermediate heating values ranging from 15.7 to 19.5 MJ/kg, demonstrating respectable thermal properties and structural interlocking. Gum Arabic produced the highest structural and moisture resistance, achieving a peak compressive strength of 206.9 kN/m² in sample Wg5 (wheat straw, Gum Arabic binder). Cassava starch still provided solid structural integrity, reaching up to 192.5 kN/m² for Ws5 (wheat straw, cassava starch binder). Coal tar binders consistently achieved the highest calorific values—peaking at 20.5 MJ/kg in 5M5Wc5—and the fastest ignition times (10.0 s) due to their high carbon and volatile density. However, the coal tar’s origin related to fossil fuels, is a cause for environmental concerns.

3.3.1 Environmental and Sustainability Trade-off of Coal Tar Binder

Although coal tar binder maximizes calorific performance (reaching a peak of 20.5 MJ/kg in 5M5Wc5) and ignition rates, its petroleum/coal origin represents a non-renewable application barrier, because it directly conflicts with clean cooking and environmental goals highlighted in Nigeria's Energy Transition Plan (NETP, 2022). Coal tar is a carbonization byproduct most likely containing carcinogenic polycyclic aromatic hydrocarbons, PAHs (such as Benzo[a]pyrene) in high concentrations (IARC, 2012), which are released upon combustion, along with heavy particulate smoke (Liu et al., 2008; WHO, 2010).

In contrast, cassava starch and Gum Arabic are renewable, non-toxic, and locally available, representing environmentally safe binders for domestic cookstove markets despite slightly lower heating values. This makes cassava starch and Gum Arabic the only sustainable, socially responsible choices of binders for briquetting especially for household combustion applications, where toxic emission control measures are difficult to implement.

3.3.3 Mechanical and Storage Properties

Binder selection governed briquette physical stability. Gum Arabic produced the highest structural and moisture resistance. The binder type was also found to govern physical storability. Gum Arabic generated superior resistance to moisture degradation and produced briquettes with the greatest resistance to water, maintaining structural integrity for 15 min while coal tar-bonded briquettes yielded the lowest. Gum Arabic produced high compressive strength in selected formulations, whereas resistance to water-induced degradation varied among individual briquette formulations. Consequently, dry mechanical strength and water resistance should be evaluated as distinct aspects of briquette storage performance

3.4 Influence of Compaction Pressure and the "Springback" Effect

3.4.1 Compaction Pressure Effect on Moisture

Phase II of the study indicated a statistically significant (Table 5) exploratory main effect of compaction pressure on moisture content ($p = 0.0017$), with the 10 MPa formulations generally exhibiting lower moisture values than the 5 MPa formulations (Figure 3).

Table 5: Phase II ANOVA Table (Feedstock Blend & Compaction Pressure)

Property	Factor Source	Sum of Sq. (SS)	Degrees of freedom (df)	F-Statistic	p-value	Significance
HHV (MJ/kg)	Feedstock Blend	8.0060	4	6.8720	0.0726	Marginally Significant (p < 0.10)
	Pressure	0.0610	1	0.2100	0.6777	Not Significant
	Residual	0.8740	3	-	-	-
Ash Content (%)	Feedstock Blend	20.3420	4	1.4350	0.3993	Not Significant
	Pressure	0.0110	1	0.0030	0.9586	Not Significant
	Residual	10.6340	3	-	-	-
Moisture Content (%)	Feedstock Blend	14.1160	4	2.7120	0.2193	Not Significant
	Pressure	154.0010	1	118.3490	0.0017	Extremely Significant
	Residual	3.9040	3	-	-	-
Ignition Time	Feedstock Blend	61.5750	4	2.8203	0.2104	Not Significant
	Pressure	3.1250	1	0.5725	0.5043	Not Significant
	Residual	-	-	-	-	-
Burning rate	Feedstock Blend	0.0074	4	8.7500	0.0528	Marginally Significant
	Pressure	0.0006	1	2.8824	0.1881	Not Significant
	Residual	-	-	-	-	-
Compressive Strength (kN/m ²)	Feedstock Blend	8250.8620	4	2.8970	0.2043	Not Significant
	Pressure	219.4510	1	0.3080	0.6175	Not Significant
	Residual	2135.7140	3	-	-	-
WRI	Feedstock Blend	115.7070	4	9.0161	0.0508	Marginally Significant
	Pressure	6.1250	1	1.9091	0.2610	Not Significant
	Residual	-	-	-	-	-

Note: Residual df = 3 for each property. The unbalanced Phase II design and absence of replication require cautious interpretation.

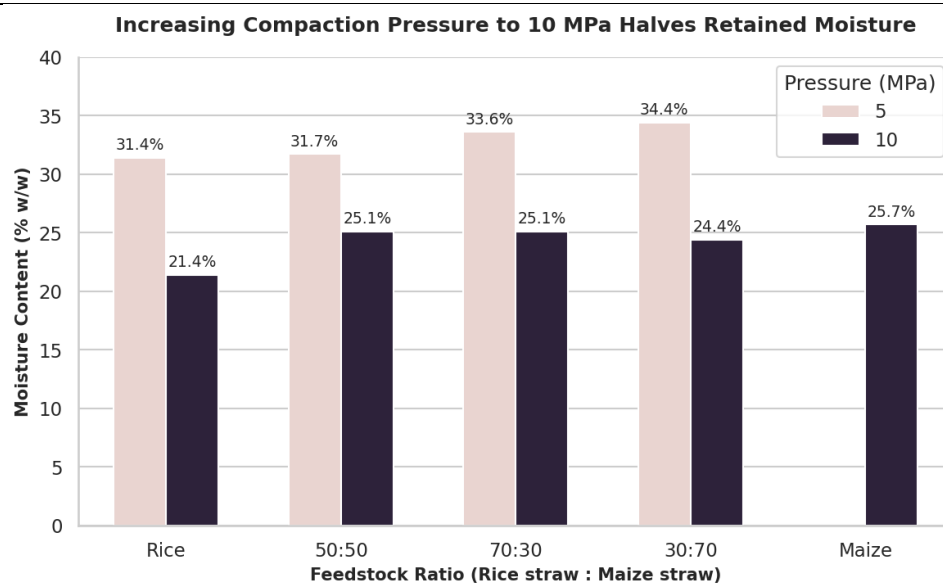


Figure 3: Effect of compaction pressure on moisture content reduction across rice-maize feedstock blend ratios in Phase II

Compaction pressure did not show a statistically significant main effect on compressive strength ($p = 0.6175$) within the limitations of the unreplicated and unbalanced design. This absence of statistical evidence should not be interpreted as proof of a specific physical mechanism. Elastic recovery or springback after ejection is a plausible explanation discussed in biomass-densification literature, but dimensional recovery, internal cracking, and post-ejection expansion were not measured in this study. Springback is therefore treated as a literature-supported hypothesis rather than an experimentally demonstrated mechanism. Doubling compaction pressure from 5 to 10 MPa compacted the particles, forcing out moisture and lowering retained moisture levels from 31.4%–34.4% down to 21.4%–25.7%. However, these values remain above the ideal bioenergy range ($<15\%$), reinforcing the need for active drying protocols as discussed in section 3.1.

3.4.2 Compressive Strength "Springback" Anomaly

Compaction pressure had no statistically significant effect on dry Compressive Strength ($p = 0.6175$, $F = 0.31$). Standard biomass densification theory dictates that higher pressure improves consolidation and strength. However, the data shows highly inconsistent changes; for example, pure maize straw (Ms10) and the 70:30 rice-maize blend (7R3Ms10) actually showed decreased compressive strength at 10 MPa compared to their 5 MPa counterparts.

This statistical insignificance ($p = 0.6175$) does not mathematically establish but is highly consistent with the hypothesis of an elastic recovery or 'springback' phenomenon typical of unheated agricultural crop residues. Because briquetting in the present study was conducted without external heating, thermal softening and flow of natural lignin were likely limited relative to heated densification processes (Kaliyan & Morey, 2009; Tumuluru et al., 2011). Highly elastic straw fibers compress under mechanical pressure but store substantial internal elastic strain energy. Upon ejection from the mould, this stored energy is released, causing immediate physical expansion. Elastic recovery or springback after briquette ejection is a plausible mechanism that may contribute to the absence of a detectable pressure effect on compressive strength. However, dimensional recovery, internal cracking and microstructural changes were not measured in the present study.

Pearson correlations (Table 6) calculated across the authoritative 18-formulation dataset showed a strong negative association between ash content and HHV ($r = -0.7$). This pattern is consistent with the observed tendency for formulations with higher inorganic residue to have lower gross energy content. HHV was also negatively associated with ignition time ($r = -0.45$), while ignition time and burning rate were positively associated ($r = 0.67$). In contrast, compressive strength and WRI showed a negligible pooled association ($r = -0.29$).

3.5 Multivariate Trade-offs and Pearson Correlation Insights

To guide solid biofuel design, the physical trade-offs must be analyzed among thermal performance, mechanical strength, and storability. For example, Gum Arabic produced high compressive strength in selected formulations, while water resistance varied substantially among formulations. Pearson correlation coefficients calculated from the verified 18-sample dataset reveal several key thermodynamic and mechanical relationships (Table 6):

1. Ash Content vs. HHV ($r = -0.70$): A strong negative correlation that mathematically validates the thermodynamic penalty of inorganic residues. Inorganic minerals (silica, etc.) do not burn, physically diluting the carbon-rich organic fraction per unit mass.
2. Compressive Strength vs. WRI ($r = -0.29$): Indicates a mechanical design conflict. High dry compressive strength (interlocking film bonds) tends to show lower wet water resistance (WRI), proving that dry mechanical integrity and wet moisture stability operate through different chemical mechanisms.

Table 6: Pearson Correlation Matrix of Briquette Properties

Property	HHV	Ash Content	Moisture Content	Ignition Time	Burning Rate	Compressive Strength	WRI
HHV	1.00	-0.70	-0.10	-0.45	-0.28	0.04	-0.15
Ash Content	-0.70	1.00	0.16	0.38	0.24	0.12	0.01
Moisture Content	-0.10	0.16	1.00	0.22	-0.24	0.15	-0.05
Ignition Time	-0.45	0.38	0.22	1.00	0.67	-0.05	0.14
Burning Rate	-0.28	0.24	-0.24	0.67	1.00	-0.13	0.08
Compressive Strength	0.04	0.12	0.15	-0.05	-0.13	1.00	-0.29
WRI	-0.15	0.01	-0.05	0.14	0.08	-0.29	1.00

4. CONCLUSION

This study presented a comparative experimental evaluation of solid biofuels produced from maize, wheat, and rice straws and their binary blends, characterized across 18 distinct formulations under compaction pressures of 5 and 10 MPa. The experimental and statistical results establish that:

- **Feedstock Blending Synergy:** Biomass composition is the primary determinant of combustion characteristics and ash behavior. While pure wheat and rice straw are penalized by high ash contents of up to 10.3% and 13.9% respectively, a 50:50 maize–wheat blend successfully buffers this ash penalty (reducing it to 7.0%–7.9%) while maintaining a high heating value between 18.2 and 20.5 MJ/kg.
- **Optimal Thermal Performance:** The 50:50 maize–wheat straw blend bonded with coal tar at 5 MPa (5M5Wc5) is the optimal thermal formulation, yielding the highest Higher Heating Value (20.5 MJ/kg), the shortest ignition time (10 s), and low ash content (7.0%).
- **Binder Governance and Sustainability:** Binders dictate mechanical durability and water resistance during storage. Gum Arabic produced high compressive strength in selected formulations, while water-resistance behaviour varied among formulations, whereas cassava starch serves as a vital green, renewable, and biodegradable alternative. Coal tar maximizes combustion characteristics but introduces severe environmental and toxicological trade-offs.
- **Pressure Limitations and Springback:** Doubling compaction pressure from 5 to 10 MPa systematically consolidates particles—reducing retained moisture from 31.4%–34.4% to 21.4%–25.7% across all formulations. The limited improvement in compressive strength at higher pressure may reflect elastic recovery effects, although this mechanism requires direct dimensional and microstructural measurements for confirmation.

In summary, high-performance solid biofuel design requires balancing thermal efficiency, mechanical durability, and storage stability rather than optimizing for a single metric. Managing these trade-offs through targeted biomass blending and binder selection offers a practical pathway for decentralized waste valorization to support Nigeria's clean energy transition.

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