Structural integrity of bagasse-based fuel briquettes: Optimisation of compaction parameters and binder formulations in Western Kenya

Ishmael Maina Makanga[1*]
Barasa H. Masinde[2]
Peter T. Cherop[3]

[1*]makangaish.im@gmail.com
[2]hmbarasa@mmust.ac.ke
[3]pcherop@mmust.ac.ke

[1,2,3]Department of Mechanical and Manufacturing Engineering, Masinde Muliro University of Science and Technology, Kakamega, Kenya

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ABSTRACT

Briquettes are not sufficiently stable to withstand breakage during handling, transport and automated feeding, which negates the engineering advantages of biomass densification. The effect of compaction pressure, processing temperature and cassava starch binder ratio on the structural integrity of sugarcane bagasse briquettes produced from four sugar mills located in Western Kenya (Mumias, Nzoia, Kabras and Busia) was studied. The Box-Behnken Design (BBD) with three factors at three levels was employed in Response Surface Methodology (RSM) and 15 experimental runs were replicated three times (45 observations). Bulk density, compressive strength, mechanical durability and diametrical tensile strength were used to quantify structural integrity. The mean bulk density, mechanical durability, compressive strength and tensile strength of the briquettes were 1.05 ± 0.06 g/cm³, 93.33 ± 3.44%, 3.60 ± 0.49 MPa and 0.63 ± 0.12 MPa respectively across the 15 design points. The second-order RSM model for compressive strength demonstrated an excellent fit ($R^2 = 0.993$; Adjusted $R^2 = 0.980$; Predicted $R^2 = 0.913$; $F(9,5) = 77.61$; $p < .001$) with a non-significant lack-of-fit ($p = .384$). Compaction pressure and binder ratio were found to be the most important linear predictors, and all quadratic terms were highly significant ($p < .001$) with the highest strength occurring at intermediate levels. The optimum operating point predicted by the model was 12.17 MPa compaction pressure, 80.00 °C processing temperature and 10.25% cassava starch binder ratio, with a predicted compressive strength of 4.35 MPa (95% CI 4.25–4.45 MPa) and bulk density of 1.14 g/cm³ (95% CI 1.13–1.15 g/cm³). These predictions are at or just above the highest observed values and have not been verified by an independent experimental run, so should be considered as model estimates until verified. The results offer a statistically modelled baseline for scaling up bagasse briquette production in humid tropical conditions without the use of capital-intensive inorganic binders that impact combustion.

Keywords: Bagasse Briquettes, Box-Behnken Design, Bulk Density, Compaction Pressure, Mechanical Durability, Response Surface Methodology, Structural Integrity

I. INTRODUCTION

In the world, experimental trials on bagasse fuel briquettes have revealed that the choice of binder, optimization of production parameters and fuel formulation are essential in determining the physical density and structural integrity of solid biofuels (Siahdashti *et al*., 2022). The optimization of the binder ratio and interaction between bagasse particle matrix has a significant effect on mechanical stability and structural resistance (Siahdashti *et al*., 2022). But biomass compaction studies show a key balance between structural integrity and additive modifications (Kularathna & Wijesekara, 2025). The incorporation of additives can change thermal profiles, but not always in a linear manner with respect to the increase of additives, highlighting the need for multi-parameter structural optimization to ensure commercial durability during handling and transport (Kularathna & Wijesekara, 2025; Setter *et al*., 2020).

Studies on agricultural residue densification in Sub-Saharan Africa have been directed towards improving the mechanical properties to be used for solid fuel standardization. Mekonen *et al*. (2024) reported that the particle size distribution, binder types and compaction ratios directly affect bulk density, shatter resistance and load-bearing capacities. The main challenges in maintaining uniformity of the structure throughout the batch production are the quality of raw materials and the ability of the binder to retain the structure (Messay *et al*., 2021). The use of individual binders does help in the cohesion of the structure, but some binders if not used properly can have a negative effect on the physical matrix

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stability, thus requiring systematic experimental controls (Yiga & Lubwama, 2020). Other organic-binder studies have reported the mechanical and combustion properties of briquettes made from bagasse blended with bush mango nutshell (Eze *et al*., 2021) and the fire characteristics of bagasse, maize cob and groundnut shell briquettes bonded with cassava starch (Okeke *et al*., 2026). However, these studies focused on feedstock blending and not on statistically modelling the combined effects of compaction pressure, processing temperature and binder ratio.

Empirical laboratory data on mechanical standardization is limited, especially in Kenya where the annual bagasse production is over 130,000 metric tons (Williamson *et al*., 2019) and in Western Kenya, the production of bagasse in the major sugar belts is more than 1,000 metric tons per day (Propellets Africa, 2023), although bagasse output and quality vary over time (Mutonyi & Andanje, 2021). Initial local assessments indicate that compaction pressure and binder selection are important factors affecting structural properties. It has been reported that the mechanical failure thresholds are much higher at higher compaction pressures and with the use of binder (Kerich *et al*., 2020; Asamoah *et al*., 2017). The average static compressive strength of the local investigations is 3.2MPa, and the average bulk density is 1.05g/cm³. The maximum densities of 1.12 g/cm³ and shatter resistance of >90% have been obtained at compaction pressures of up to 12 MPa (Gebrezgabher *et al*., 2018) and the cassava starch formulations of 15% gave maximum compressive strengths of 4.0 MPa. The use of locally produced briquettes has also been demonstrated to alleviate environmental pressure in urban Kenya (Njenga *et al*., 2013) and to support livelihoods, further supporting the need for standardised bagasse briquettes.

One of the major limitations of the existing literature is the use of a One-Factor-at-a-Time (OFAT) experimental design (Towett, 2024). The interaction effects between compaction pressure, processing temperature and binder ratio are complex and cannot be captured by single variable evaluations (Towett, 2024; Chirchir *et al*., 2013). To create reliable predictive models for scaling to industry, understanding these multi-variable interdependencies is important and can be achieved using Response Surface Methodology (RSM) (Towett, 2024).

1.1 Statement of the Problem

Sugar factories in Western Kenya produce more than 1 000 MT of sugarcane bagasse per day with less than 5% being valorised into standardised fuel briquettes (Propellets Africa, 2023). The main technical challenges that hinder the use of these briquettes are related to their structural integrity: The bulk density of the briquettes produced by the existing compression methods ranges from 0.95 g/cm³ to 1.05 g/cm³, which is below the ISO 17225-2 benchmark of ≥1.10 g/cm3 (Nganko *et al*., 2024). Poor selection and proportioning of binders result in poor compressive strength values (<2.0 MPa) which make the briquettes liable to crumbling, cracking and mechanical failure during storage, loading and transportation (Nganko *et al*., 2024). Artisanal producers use heuristic "trial-and-error" methods because of the absence of locally available, experimentally validated data on the combined effects of compaction pressure, processing temperature and ratio of binder under humid tropical conditions (25-35 °C, 60-80%RH). The product quality is not uniform, which is a restriction to its commercialization and industrial use without statistically modelled processing parameters. Therefore, this study seeks to systematically analyse and optimise the compaction pressure, processing temperature and binder ratio using Response Surface Methodology (RSM) with a Box-Behnken Design (BBD) to establish the standards of structural integrity for bagasse briquette production in Western Kenya that can be predicted.

II. LITERATURE REVIEW

2.1. Empirical Review

2.1.1 Bulk Density of Bagasse Briquettes

The most fundamental criterion for commercialization of bagasse briquettes is the structural integrity of the briquettes, which is measured by bulk density, compressive strength and mechanical durability of the briquettes and is indicative of the resistance of the briquettes to physical attrition during handling, transportation and automated feeding in cookstoves (Kaliyan & Morey, 2009). Densification is the process of making solid fuel units of high structural properties from the loose, low-density agricultural bagasse. The mechanical structure and lamellar alignment of bagasse can be improved by advanced processing and thermochemical treatments, which can lead to higher bulk density, up to 340 kg/m³ (Valix *et al*., 2017; Wang *et al*., 2024).

The fuel blocks obtained from high-pressure briquetting of raw sugarcane bagasse can have high bulk densities (1022.44 kg/m³), compressive strengths up to 150.82 N/mm and mechanical durability ratings up to 99.29% (Brunerová *et al*., 2020). Bagasse has also demonstrated good performance as a waste-material binder: Khaya senegalensis pellets bonded with bagasse achieved a maximum density of 0.967 g/cm³, mechanical durability of 99.71%, shatter resistance of 98.85% and water resistance of 98.35% (Ismail *et al*., 2023).

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2.1.2 Effect of Compaction Pressure on Mechanical Performance

The compaction pressure is one of the most important factors that affect the mechanical resistance, structural density and load-bearing capacity of biomass briquettes (Afra *et al*., 2021). As the compaction force is increased, the void spaces between the particles are decreased, which results in mechanical interlocking, higher bulk density and higher axial compressive strength (Brunerová *et al*., 2020; Reis-Portilho *et al*., 2020). The high-pressure compaction leads to higher packing density of the particles and the production of strong briquettes which can be transported over long distances and stored in bulk (Reis-Portilho *et al*., 2020).

But there are limits to densification dynamics, as beyond the optimum pressure, there is a decrease in the density and mechanical strength (João *et al*., 2023). Sub-Saharan Africa studies also show that the use of organic binders such as cassava starch and high compaction force has a significant effect on the structural cohesion of the briquettes, resulting in denser briquettes with high mechanical resistance (Kerich *et al*., 2020; Okot *et al*., 2018). For example, when the compaction pressure was optimized at 5 kN, the briquettes were made using wastepaper and clay binders, and the resulting briquettes had a better compressive strength (Inuma *et al*., 2023).

2.1.3 Effect of Processing Temperature on Particle Bonding

The processing temperature plays a significant role in the physical, chemical and structural properties of bagasse briquettes (Mamvura & Danha, 2020). The controlled thermal conditioning during the pre-drying or the compaction decreases the moisture content, the hygroscopicity and increases the structural stability (Alfian *et al*., 2024; Ivanovski *et al*., 2022). The drying of bagasse at 200 °C results in a low amount of moisture content of about 4.47%, which meets the national solid fuel standard (Alfian *et al*., 2024). The energy density and the stability of the structure of the material during storage can be improved by pre-heating or torrefaction up to 260-275 °C (Ivanovski *et al*., 2022; Manatura, 2020). Torrefaction followed by briquetting has also been demonstrated to decrease the hygroscopicity and increase the calorific value of bagasse–eucalyptus briquettes (Costa *et al*., 2019) and to alter the physicochemical properties and combustion performance of bagasse briquettes (Torres *et al*., 2026).

However, there are some drawbacks, and thermal limits need to be carefully managed. The high processing temperature can cause thermal degradation, loss of mass and embrittlement of the matrix, which can have a negative impact on the final mechanical stability and structural strength of the briquettes (Su *et al*., 2020).

These studies collectively indicate that the temperatures that most favorably affect the fuel properties (200-275 °C) are well above the 60-100 °C range of interest for starch-bonded briquetting, where the primary effect of heat is to gelatinise and soften the binder. There is therefore little evidence on the interaction between moderate processing temperatures and compaction pressure and binder content, and this is the range investigated in the present study.

2.1.4 Effect of Binder Type and Concentration on Cohesion

The right choice of binder type and the ratio of the binder to the bagasse is important to create a good inter-particle adhesion in the bagasse matrix. Binders are used to create a bridge-like structure, to fill holes and to improve the compressive strength and compactness (Siahdashti *et al*., 2022). Lignin- and starch-based binders have a significant effect on increasing the structural density and reducing the permeability (Siahdashti *et al*., 2022).

The studies conducted in Sub-Saharan Africa have been based on locally available binding materials like cassava starch, clay, molasses, wastepaper and cow dung (Mekonen *et al*., 2024; Sweya *et al*., 2024). The tumbling resistance and rigidity are enhanced by clay binders, and the fibrous wastepaper and starch formulations enhance the compressibility strength and density (Sweya *et al*., 2024). An optimized formulation with 9.12% clay and 12.57% wastepaper, for example, had a compressive strength of 6.47 MPa (Inuma *et al*., 2023). Likewise, using Taguchi optimization technique on binder-feedstock ratio resulted in the production of high-density briquette of 904kg/m³ (Okwara *et al*., 2023).

Onchieku *et al*. (2012) in Kenya discovered that the mixture of one part molasses, one part clay and 40 parts carbonised bagasse pressed at 0.50 N/mm2 met the household charcoal-briquette specifications, while Kerich *et al*. (2020) in Kenya reported that cassava starch mixed with higher compaction pressure produced stronger rice husk–bagasse briquettes. In all these studies, there is a consistent trade-off: Clay increases rigidity and tumbling resistance (Sweya *et al*., 2024) but also adds incombustible mineral matter, which increases ash residues (Messay *et al*., 2021), while organic binders like starch, molasses and wastepaper increase strength and density but also contribute to the heating value (Mekonen *et al*., 2024; Obi *et al*., 2022). For this reason, cassava starch was chosen as the binder for the optimisation in this report. It is grown and processed extensively in Western Kenya, it burns easily and leaves little ash, and it gelatinises at moderate temperatures, so its bonding behaviour is expected to respond to the 60–100 °C processing range studied. In the larger study

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from which this paper is taken, the cassava starch-bound briquettes also produced less residual char and ash (11.3–15.4%) than the clay-bound briquettes (up to 23.3%).

To enable comparisons between different studies, it is important to standardize the methods used for assessing binders, and to ensure that mechanical strength is maximized while structural performance is not sacrificed (Obi *et al*., 2022).

2.2 Response Surface Methodology and Selection of Experimental Design

Response Surface Methodology (RSM) is a method that fits a second-order polynomial to the experimental data obtained from the designed experiments, allowing the estimation of linear, quadratic (curvature) and two-way interaction effects, and the location of an optimum, with significantly fewer runs than a full three-level factorial design (Myers *et al*., 2016). Response surface studies that model compaction pressure and binder content together have been reported for other feedstocks, such as carbonised sawdust (Nganko *et al*., 2024). The central composite design (CCD) and the Box-Behnken design (BBD) are the two most employed designs for this purpose. A rotatable CCD requires 17-20 runs at five levels per factor, with axial points outside the factorial range (in coded units, ±1.68); in this study, that would have involved pressures of approximately 1.6 and 18.4 MPa, temperatures of approximately 46 and 114 °C, and binder ratios of approximately 1.6% and 18.4%. The BBD requires only 15 runs, sets the runs at the mid-points of the edges of the design cube and omits the corner combinations where all factors are simultaneously at their extreme levels (Box & Behnken, 1960; Ferreira *et al*., 2007). The BBD was therefore preferred as it required fewer runs and maintained all the runs within the ranges of 5–15 MPa, 60–100 °C and 5–15% which were considered practical for manual pressing and starch bonding.

There are also limitations of RSM and the BBD that affect the interpretation of this study. The fitted polynomial is a local approximation and should not be extrapolated beyond the range of the experiments. The BBD does not have runs at the corners of the design cube; this means that predictions will not be as accurate near the corners as they will be near the centre. Finally, there are only 10 terms in the model and 15 design points, so there are only five residual degrees of freedom and a single anomalous run can have a strong effect on the fitted coefficients; predicted optima should be confirmed by experiment (Ferreira *et al*., 2007; Myers *et al*., 2016).

2.3 Research Gap

A comparison of these studies reveals three points. First, the properties reported are not directly comparable because of the differences in feedstocks, binders, presses and test methods (Obi *et al*., 2022): bagasse briquettes achieved 1022 kg/m³ and 99.29% durability under high-pressure briquetting (Brunerová *et al*., 2020), while African formulations with mixed binders achieved about 805–904 kg/m³ (Mekonen *et al*., 2024; Okwara *et al*., 2023). Second, the evidence on process parameters is partially contradictory: higher pressure led to higher strength and density in most studies (Afra *et al*., 2021; Kerich *et al*., 2020), but the improvement was limited after a certain point (João *et al*., 2023), and higher temperature of thermal treatment led to better fuel properties (Alfian *et al*., 2024; Ivanovski *et al*., 2022), but excessive heat can reduce the strength of the matrix (Su *et al*., 2020). Third, most studies varied one factor at a time (Towett, 2024) or estimated main effects only, e.g., Taguchi arrays (Okwara *et al*., 2023), and so could not explain these optima or the interactions behind them. The present study aims to fill this gap by modelling the main, quadratic and interaction effects of compaction pressure, processing temperature and cassava starch ratio on the structural integrity of bagasse briquettes from the four main mills in Western Kenya.

III. MATERIALS AND METHODS

3.1 Study Site and Feedstock Sourcing

The raw sugarcane bagasse was obtained from four sugar mills namely Mumias, Nzoia, Kabras and Busia Sugar Companies in the Western Kenya. The reasons for the selection of these locations were their high production capacity of bagasse of more than 1000 metric tons per day. The processing equipment listed in Section 3.2 was used for sample preparation and briquetting while the physical–mechanical evaluations were conducted in the laboratory facilities in Kakamega County, Western Kenya, which were close to the four mills.

3.2 Processing Equipment and Testing Apparatus

The following equipment and instrumentation were used for sample preparation and mechanical testing:

Pulverizer (Retsch SM100): Used to grind the raw bagasse in a uniform particle size of less than 2 mm.

Drying Oven (Memmert UN55): For thermal drying of the feedstock to obtain a basic moisture control.

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Digital Scale (Ohaus SPX2202): Precision weighing scale (±0.01 g) for gravimetric measurements.
Moisture Analyser (Ohaus MB120): For measuring moisture content of the finished briquettes.
Manual Briquette Press: Densification unit that can be used to apply compaction pressures up to 20 MPa.
Universal Testing Machine (Instron 3369) with load cells and data acquisition software to measure mechanical strength properties in both axial and lateral loading.

3.3 Feedstock Preparation and Conditioning

The locally available binders (cassava starch, molasses and clay) were initially screened, and cassava starch and clay were selected due to their binding efficacy, cost and moisture resistance. In the Box-Behnken experiments reported in this paper, however, only cassava starch was used: the binder ratio (BR) factor is the percentage by weight of cassava starch only, and no clay or starch–clay blends were used in the structural-integrity design. The raw bagasse was comminuted in a Retsch SM100 pulveriser and sieved through a 2 mm screen (particle size < 2 mm, mostly in the range of 0.5–1.0 mm). The same milling and screening was performed for each batch, and particle size was not an experimental factor, the full particle size distribution (D10, D50, D90) was not measured. The milled bagasse was well mixed with the binder at the weight fraction specified for each run. The moisture content of the mixture was adjusted to a target of 15% by adding a calculated amount of water to the oven dried (Memmert UN55) feedstock and equilibrated in sealed containers for 24 hours before briquetting to ensure uniform moisture content in all the samples. The moisture content of the conditioned mixture after equilibration was not recorded separately, but the moisture content of the finished briquettes was measured with the Ohaus MB120 moisture analyser and is reported in Section 4.1.1.

3.4 Design of Experiments

To evaluate and optimize the densification parameters, a Response Surface Methodology (RSM) framework with three factors and three levels Box-Behnken Design (BBD) was developed by using the Minitab 21 software. The independent variables investigated were: The Box-Behnken design was selected over a central composite design because it requires fewer runs (15 versus 17–20 for three factors), uses only three levels of each factor, and contains no runs at the extreme corners of the design cube where all three factors are simultaneously at their highest or lowest levels (Section 2.2).

Compaction Pressure (CP): Evaluated at 5 MPa (low, -1), 10 MPa (medium, 0), and 15 MPa (high, +1).
Processing Temperature (PT): Evaluated at 60 °C (low, -1), 80 °C (medium, 0), and 100 °C (high, +1).
Binder Ratio (BR): Evaluated at 5% (low, -1), 10% (medium, 0), and 15% (high, +1) by weight.

The design matrix consisted of 15 different combinations of experiments (12 edge mid-point combinations and three centre-point replicates). Each experiment was repeated three times to obtain 45 experimental observations and the average of the three replicates at each design point was used for model fitting.

Table I
Design of Experiment

Factor	Parameter	Low Level (-1)	Medium Level (0)	High Level (+1)
CP	Compaction Pressure (MPa)	5	10	15
PT	Processing Temperature (°C)	60	80	100
BR	Binder Ratio (% by weight)	5	10	15

3.5 Mechanical and Physical Testing Protocols

3.5.1 Compressive Strength Test

Instron 3369 Universal Testing Machine was used to determine the Uniaxial Compressive Strength. The individual briquettes were placed in between flat rigid platens and axially compressed at a constant crosshead speed of 5 mm/min until the ultimate structural failure. The maximum force at failure (F_{max}) was automatically recorded and the compressive strength (σ_c, MPa) was calculated from Equation (1):

$$\sigma_c = \frac{F_{\max}}{A}$$

where F_{max} is the maximum force at failure (N) and A is the cross-sectional area of the briquette (mm^2). The force is in newtons and the area in square millimetres, so σ_c is obtained directly in N/mm^2, which is numerically equal to MPa. The briquette was loaded along its cylinder axis, and A is the area of its circular end face ($A = \pi D^2/4$).

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3.5.2 Diametrical tensile Splitting Strength Test

The diametrical compression loading was performed on Instron 3369 Universal Testing Machine to test the briquettes for resistance to cracking and brittle fracture. Cylindrical briquettes were subjected to lateral compression between loading platens until failure occurred, with the briquette being horizontally placed between the platens. Based on Equation (2), the tensile splitting strength (σ_t, MPa) was calculated by the following standard elastic failure formula:

$$\sigma_t = \frac{2P_{\max}}{\pi DL}$$

where P_{max} is the maximum splitting load applied (N), D is the diameter of the briquette (mm) and L is the length of the briquette (mm). L is the length of the cylinder along its axis. The cylinder was placed with its axis parallel to the faces of the platen and the compressive load was applied along a diameter throughout the length of the specimen, and failure was by splitting along the loaded diametral plane. In N and D and L in mm, Pmax and σ_t in N/mm² (MPa) are as in Equation (1).

3.5.3 Bulk Density, Mechanical Durability and Moisture Content of the Briquettes

Bulk Density: Obtained immediately after fabrication by measuring the mass of individual samples on Ohaus SPX2202 scale and calculating the physical dimensions with the help of digital calipers to find mass to volume ratio (g/cm3).

Mechanical Durability: Tested in a standard tumble machine. The briquettes were tumbled agitated for a predetermined time, sieved and the mass of the briquette structure that remained intact was determined. Durability (%) was the percentage of the initial mass that remained after the tumbling process.

Moisture Content: The moisture content of the finished briquettes was determined using Ohaus MB120 moisture analyser.

In this study, shatter index (drop-test resistance) was not determined. Structural integrity was thus defined as bulk density, compressive strength, diametrical tensile strength and mechanical durability.

3.6 Statistical Analysis and Optimization of the Data

The experimental data were recorded as soon as the physical testing was done. Minitab 21 was used to perform Analysis of Variance (ANOVA) to determine the main, quadratic and two-way interaction effects of compaction pressure, processing temperature and binder ratio on the responses at $p<0.05$. The response data were fitted to second order polynomial mathematical models, which were used to draw predictive surface equations and to find the optimum processing parameters for the maximum structural integrity. A complete second order (quadratic) model with all three linear, three quadratic and three two-way interaction terms was fitted to the mean response of each of the 15 design points, with five residual degrees of freedom. No stepwise or backward elimination was performed; non-significant terms were kept in the model to ensure that the model was hierarchical, and the lack-of-fit test and optimisation were performed on the full second order model (Myers *et al*., 2016). The optimum settings were found using the Minitab response optimiser and 95% confidence intervals were calculated for the predicted mean responses at the optimum.

IV. RESULTS AND DISCUSSION

4.1 Results

4.1.1 Structural Integrity Characteristics

The physical and mechanical properties of the bagasse briquettes were assessed and revealed good physical and mechanical properties for the four structural integrity parameters measured. Bulk density spanned from 0.94 g/cm³ to 1.13 g/cm³, with a mean value of 1.05±0.06g/cm3. Mechanical durability ranged between 87.3% and 98.1%, with a mean of 93.33±3.44%. The UCS values varied between 2.8 and 4.3 MPa with a mean value of 3.60±0.49 MPa. The tensile strength values obtained from diametrical tensile splitting tests varied from 0.44 to 0.81 MPa with an average value of 0.63±0.12 MPa. The moisture content of the finished briquettes varied from 8.70% to 14.70% with an average of 10.93 ± 1.82%.

Table II

Structural Integrity Characteristics

Structural Integrity Parameter	Minimum	Maximum	Mean	Standard Deviation
Bulk Density (g/cm³)	0.94	1.13	1.05	0.06
Mechanical Durability (%)	87.3	98.1	93.33	3.44
Compressive Strength (MPa)	2.8	4.3	3.60	0.49
Diametrical Tensile Strength (MPa)	0.44	0.81	0.63	0.12
Moisture Content of Briquettes (%)	8.70	14.70	10.93	1.82

Summary statistics of the 15 design-point means (N = 15). In this study, shatter index was not measured.

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A second order polynomial Response Surface Methodology (RSM) regression model was used to model the compressive strength within the experimental design space. The model demonstrated statistical fit (R2=0.993, Adjusted R2=0.980, Predicted R2=0.913, F (9,5) = 77.61, p<0.001). The lack-of-fit test was statistically non-significant (p=0.384) and thus confirmed the model fitness for the purpose of prediction. The Variance Inflation Factors (VIF) were all equal to 1.00 which indicated that the design was orthogonal with no multicollinearity.

The second order polynomial equation that can be used to predict the compressive strength (Equation 3), with its coefficients and their significance given in Table III, is:

$$\text{Compressive Strength } (MPa) = -5.917+0.546(CP)+0.123(PT)+0.386(BR)-0.018(CP^2)-0.0007(PT^2) - 0.018(BR^2)-0.001(CP \times PT)-0.001(CP \times BR) \quad (3)$$

The compaction pressure (CP) (MPa), processing temperature (PT) (°C) and binder ratio (BR) (%) are represented by the parameters.

The coefficients in Equation (3) and Table III are rounded for presentation. The predictions reported in this paper (e.g., 4.35 MPa at the optimum) were calculated in Minitab using the unrounded coefficients; the rounded coefficients used in Equation (3) will yield slightly different predictions (e.g., 4.39 MPa at the optimum).

Table III

Structural Integrity Response Surface Model is a method for modeling the response surface of a structure.

Term	Unstandardized Coefficient (b)	Standard Error (SE)	t-value	p-value (exact)
Intercept	-5.917	0.747	-7.93	.0005
CP (MPa)	0.546	0.043	12.76	< .0001
PT (°C)	0.123	0.015	8.02	.0005
BR (%)	0.386	0.043	9.02	.0003
CP^2	-0.018	0.001	-12.55	< .0001
PT^2	-0.0007	0.00009	-7.72	.0006
BR^2	-0.018	0.001	-12.55	< .0001
CP × PT	-0.001	0.0003	-2.88	.035
CP × BR	-0.001	0.001	-0.72	.504

b = unstandardised coefficient (in actual (uncoded) units); SE = standard error. The five residual degrees of freedom of the model were used to recalculate exact two-tailed p-values from the t-values, so that the intercept (t = −7.93) and PT^2 (t = −7.72) terms are significant at p < .001, as previously reported. The same standard errors and t-values for CP^2 and BR^2 are not a transcription error, but rather a property of the design: CP and BR were studied over the same range (5–15, step 5) and were in the same position in the Box-Behnken matrix, so their quadratic coefficients have the same standard errors, and their estimated coefficients were also the same. Coefficients and standard errors are rounded, so that b/SE calculated from the tabulated values does not exactly match the t-values calculated from the unrounded estimates. The PT × BR term was fitted as part of the full quadratic model (hence $F(9, 5)$), but its estimated coefficient was zero to the reported precision, so it is not tabulated. The non-significant CP × BR term (p = .504) was retained as explained in Section 3.6 to retain the full second-order model on which the lack-of-fit test and optimisation are based; it does not affect the conclusions about which effects are significant.

The overall model, goodness-of-fit and lack-of-fit statistics for the compressive strength model are presented in Table IV.

Table IV:

Model Summary Statistics for Compressive Strength

Statistic	Value
R^2	0.993
Adjusted R^2	0.980
Predicted R^2	0.913
Model F (df = 9, 5)	77.61
Model p-value	< 0.001
Lack-of-fit p-value	0.384
Residual degrees of freedom	5
Variance inflation factors (all terms)	1.00

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Statistics are for the complete second order model fitted to the 15 design-point means.

4.1.2 Variable Interactions and Mechanistic Interpretation

The regression coefficients indicate that compaction pressure (t = 12.76, $p < 0.001$), processing temperature (t = 8.02, $p < 0.001$) and binder ratio (t = 9.02, $p < 0.001$) have positive linear effects on compressive strength. The quadratic terms (CP^2, PT^2, and BR^2) had statistically significant negative coefficients ($p \leq 0.001$), indicating a curvilinear response surface with a maximum compressive strength at intermediate levels of the factors.

This curvilinear behavior is physically related to the over-saturation of the binder, binder plasticization and biomass particle fracture caused by the excessive compaction forces. If applied pressures are too high, they may break the solid biomass structure and result in elastic spring-back when the pressure is removed, reducing the contact bonds between particles. Too much binder fractions interfere with the continuous solid bridge formation between particles.

A statistically significant two-way interaction was found between compaction pressure and processing temperature ($CP \times PT$: t = -2.88, p = 0.035). This indicates that the effect of compaction pressure on strength depends on the thermal processing temperature. The compaction force needed to produce a cohesive matrix is dependent on the amount of thermal conditioning because of the soft, plasticized nature of the binder. However, two-way binder interactions ($CP \times BR$ and $PT \times BR$) were not statistically significant ($p > 0.05$).

4.1.3 Optimisation and Predicted Optimum

Optimisation of the fitted models resulted in an optimum at compaction pressure of 12.17 MPa, processing temperature of 80.00 °C and cassava starch binder ratio of 10.25% (Table V). The predicted mean compressive strength at these settings was 4.35 MPa (95% CI 4.25–4.45 MPa) and the predicted mean bulk density, from the corresponding second-order model for bulk density, was 1.14 g/cm³ (95% CI 1.13–1.15 g/cm³; 95% prediction interval 1.12–1.17 g/cm³).

Table 5:

Optimum Processing Parameters and Predicted Structural Properties

Parameter / Response	Optimal Setting / Predicted Value	95% CI
Compaction pressure (MPa)	12.17	–
Processing temperature (°C)	80.00	–
Binder ratio (% cassava starch)	10.25	–
Predicted compressive strength (MPa)	4.35	4.25–4.45
Predicted bulk density (g/cm³)	1.14	1.13–1.15

CI = confidence interval for the mean response at the optimum settings. Values are model predictions and were not confirmed by an independent experimental run.

Both the predicted values are slightly higher than the highest values obtained for the 15 design points (4.3 MPa and 1.13 g/cm³). This is because the optimum combination of factors was not one of the design points and is within the experimental region (all three factors are within their −1 to +1 coded limits), so the prediction is an interpolation in factor space rather than an extrapolation. Both confidence intervals, however, contain the best observed values, and the predicted gain over the best observed run is small and not statistically different from it. In this study, no confirmation experiment at the optimum settings is reported, and these predicted values have not been confirmed experimentally; they should be treated as model estimates, and confirmation experiments at the optimum settings should be performed before the settings are adopted in production.

4.2 Discussions

4.2.1 Structural Integrity Characteristics

The mean bulk density obtained (1.05±0.06 g/cm3) directly contributes to increase the volumetric energy density, to increase the burning time, to decrease the volumetric footprint during transport and logistic. Meanwhile, the mechanical durability (93.33±3.44%), compressive strength (3.60±0.49 MPa) and diametrical tensile splitting strength (0.63±0.12 MPa) exhibit a consistent internal structural matrix. From practical point of view, these physical and mechanical parameters suggest that the fuel briquettes are likely to withstand stresses during the postproduction process, in the warehouse and during transportation without physically degrading or affecting the combustion process, thus maintaining the quality of the fuel before use.

The results are in good agreement with the literature on biomass densification and structural optimization. The bulk density observed (1.05g/cm3) is close to the value of 1.022g/cm3 (1022.44 kg/m3) reported by Brunerová *et al*. (2020) for high-pressure briquetting but slightly higher than the value of 0.967 g/cm3 reported by Ismail *et al*. (2023) for Khaya

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senegalensis pellets bonded with waste-material binders including bagasse. Moreover, the average mechanical durability of 93.33% is in line with the values of mechanical durability reported by Ismail *et al*. (2023) (up to 99.71%) and Brunerová *et al*. (2020) (99.29%). These are important preconditions for commercial viability, as noted by Kaliyan and Morey (2009). The improved compressive and tensile properties also support the findings of Wang *et al*. (2024) and Valix *et al*. (2017), who showed that highly oriented carbon matrices can be achieved through advanced densification, which can withstand long use times and are comparable to conventional solid fossil fuels. The comparison with the ISO 17225-2 benchmark of ≥ 1.10 g/cm³ cited in Section 1.1 is less favourable: the mean bulk density across the design (1.05 g/cm³) is below this benchmark, and only some design points (maximum 1.13 g/cm³) exceeded it. The optimum (1.14 g/cm³; 95% CI 1.13–1.15 g/cm³) is predicted to be above the benchmark, which means that the target can only be achieved if the process is run near the optimum; briquettes produced under arbitrary settings within the studied range should not be assumed to meet the target.

These physical and mechanical properties from engineering point of view are a sign of successful optimization of densification parameters, resulting in the production of a fuel matrix suitable for the requirements of industrial/commercial application. The high compressive and tensile strength suggests that there is intermolecular bonding and interlocking of particles in the matrix. This mechanical cohesion is required to resist static compressive stresses in stacked storage, and dynamic shear stresses in automated feeding in improved cookstoves and industrial boilers. These results therefore help to design scalable biomass valorisation systems for the renewable energy sector, aiming to minimize post-production fines, maximize thermal efficiency, maximize logistical feasibility and maximize commercial scalability.

4.2.2 Structural Integrity Response Surface Model

The high R2 (0.993), the close agreement between the adjusted (0.980) and predicted (0.913) R2 values and the non-significant lack-of-fit (p = .384) suggest that the second order model is adequate to describe compressive strength within the experimental region. The main, quadratic and interaction terms of these factors are statistically evaluated, and it is found that the mechanical integrity is controlled by the compaction pressure, processing temperature and binder ratio in non-linear dynamics.

The negative sign of all the quadratic terms (CP2, PT2, BR2) indicate that the compressive strength has a curvilinear relationship, that is, it increases with the increase in the factor level up to a certain level and then decreases. The first increment of process parameters can enhance the structure cohesion by the interlocking of the particles and the activation of the binder. However, when the optimal thresholds are surpassed, physical degradation mechanisms are activated: fracturing of biomass particles at high compaction forces, over-saturation of the binder or too much plasticization of the binder. Moreover, the significant CP × PT interaction (p = 0.035) shows that the mechanical densification efficiency is related to the thermal inputs, and that they need to be balanced in order to obtain maximum structural resilience.

The outcomes of these empirical modelling are consistent with the known thermo-mechanical biomass densification principles, which are based on optimisation of parameters to maximise the mechanical strength. The positive linear effect of compaction pressure is consistent with the results of Brunerová *et al*. (2020) who also reported that the compaction pressure is important to achieve compressive resistance. On the other hand, the decrease of strength at high pressures observed is consistent with known densification mechanisms: constituent particles are fractured and will exhibit elastic spring-back when the pressure is removed.

The statistical significance of binder ratio is consistent with the results obtained by Ismail *et al*. (2023) and Wang *et al*. (2024) who showed that the inclusion of binders can enhance the structural orientation and mechanical durability, however, excessive binder fraction will negatively affect the construction of a continuous solid bridge between the particles. Furthermore, the interaction between compaction pressure and processing temperature (CP×PT, p = 0.035) agrees with thermochemical assessments carried out by Valix *et al*. (2017) which showed that thermal conditions have an influence on the plasticization and binding performance of the biomass and therefore on the compaction pressure needed to obtain a dense fuel matrix.

Once the optimum of the second order RSM model is verified by experiments, it can be used to guide process control and scale-up. The model gives a quantitative description of the operational boundaries and multi-variable interactions of pressure, temperature and binder ratio, which can be used as a basis for automated feedback control systems for industrial briquetting equipment. This predictive capability could enable densification to be performed without excessive compaction force or thermal input, while ensuring structural integrity and minimizing specific energy consumption (SEC), operational costs and equipment wear. Thus, the production of briquettes could shift from trial and error to model based settings to produce standardized briquettes that satisfy the durability criteria for commercial storage, long-distance transport and automated feeding.

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V. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

Based on the experimental results and statistical modelling of the structural integrity optimization of bagasse-based fuel briquettes, the following conclusions are drawn:

i. *Structural Integrity Characteristic*: The mean bulk density, mechanical durability, compressive strength and diametrical tensile strength of the bagasse briquettes were 1.05 ± 0.06 g/cm³, 93.33 ± 3.44%, 3.60 ± 0.49 MPa and 0.63 ± 0.12 MPa respectively across the 15 design points. The mean bulk density is lower than the ISO 17225-2 requirement of ≥ 1.10 g/cm³, with only some design points meeting this requirement (maximum 1.13 g/cm³).

ii. *Model adequacy*: The second order Response Surface Methodology (RSM) model was found to be excellent and adequate for prediction (R^2 = 0.993, Adjusted R^2 = 0.980, Predicted R^2 = 0.913; lack-of-fit p = .384), and the compaction pressure and binder ratio were the most significant linear factors affecting the axial compressive strength.

iii. *Non-Linear Quadratic Dynamics*: Quadratic effects across process parameters were highly significant ($p < 0.001$) and showed that compressive strength reached a maximum at intermediate factor levels, before decreasing due to physical limitations (e.g. over-saturation of the binder) or physical constraints on biomass particles (e.g. fracturing under high mechanical stresses).

At the model-predicted optimum (12.17 MPa, 80.00 °C and 10.25% cassava starch), the predicted compressive strength is 4.35 MPa (95% CI 4.25–4.45 MPa) and the predicted bulk density is 1.14 g/cm³ (95% CI 1.13–1.15 g/cm³), which would meet the ISO 17225-2 density benchmark. These values are model predictions and have yet to be confirmed by experiment.

5.2 Recommendations

Based on the results of the experimental optimization and statistical modeling of bagasse briquette structural parameters, the following recommendations are suggested, taking into consideration the laboratory scale of the study and the fact that the optimum has not yet been confirmed experimentally (Section 4.2.3):

i. *Process Parameter Standardization*: The optimum value obtained from the study (compaction pressure of 12.17 MPa, processing temperature of 80.00 °C and cassava starch binder ratio of 10.25%) should be confirmed by replicated confirmation runs and pilot-scale trials before adoption so that commercial briquette producers can standardise the value in their regular production process.

ii. *Equipment Manufacturers & Facility Operators*: Industrial briquetting presses should be equipped with calibrated measurement gauges and control systems. Monitoring these operational boundaries should help producers to consistently achieve the predicted bulk density of 1.14 g/cm³ and compressive strength of 4.35 MPa, once these have been verified experimentally.

Further Research: Future work should include (i) confirmation runs at the predicted optimum and reporting of observed against predicted values; (ii) measurement of shatter index, particle size distribution and moisture content of the conditioned feedstock; and (iii) extension of the model to other locally available binders and to pilot-scale continuous presses.

Declaration of Interest

The authors declare that they do not have any known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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