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Predictive modeling of density-controlled mechanical strength in biomass briquettes produced from candlenut shell and tamarind peel

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ABSTRACT

The utilization of agricultural waste for biomass briquette production offers a sustainable approach to renewable energy development. This study investigated the effect of mixture ratio between candlenut shell charcoal (*Aleurites moluccanus*) and tamarind peel (*Tamarindus indica* L.) on the physical and mechanical properties of biomass briquettes, with particular emphasis on density and compressive strength. Briquettes were produced using five mixture ratios (1:3, 1:2, 1:1, 2:1, and 3:1, w/w) and evaluated for moisture content, density, and compressive strength. The results showed that moisture content remained low and relatively constant across all treatments (≈6%), while density and compressive strength exhibited significant dependence on mixture ratio. Density displayed a nonlinear trend with a clear maximum near the 1:1 ratio, whereas compressive strength increased linearly with density. Based on these relationships, a semi-empirical predictive model was developed by coupling a quadratic density–ratio model with a linear density–strength model. The integrated model successfully captured the observed experimental trends and identified an optimal mixture region consistent with the highest mechanical performance. The proposed model provides a simple and physically meaningful framework for predicting briquette strength from mixture composition, enabling preliminary formulation optimization with reduced experimental effort. This approach supports efficient utilization of agricultural residues for sustainable solid biofuel production.

Keywords: biomass briquette, agricultural waste, density, compressive strength, predictive model.

INTRODUCTION

The increasing demand for energy, coupled with growing environmental concerns, has intensified the search for sustainable and renewable energy sources. Biomass-derived solid fuels have gained considerable attention as alternatives to fossil fuels due to their renewability, lower net carbon emissions, and potential for utilizing agricultural residues that would otherwise be discarded or openly burned. Recent studies have emphasized the importance of optimizing biomass briquette production using locally available feedstocks to enhance sustainability, resource efficiency, and fuel performance while reducing environmental impacts (Silas et al., 2025). Among these alternatives, biomass briquettes offer practical advantages, including ease of handling, relatively stable combustion, and suitability for household and small-scale industrial applications.

Indonesia, as an agrarian country, generates large quantities of agricultural waste each year. Candlenut shell (*Aleurites moluccanus*) and tamarind peel (*Tamarindus indica* L.) are two such residues that remain underutilized despite their favorable characteristics for solid biofuel production. Candlenut shell is rich in carbon and forms rigid charcoal particles, making it suitable as a primary energy-bearing component. In contrast, tamarind peel contains fibrous and organic constituents that can contribute to binding and structural cohesion during briquette formation. Previous studies have explored the use of candlenut shell and coconut coir in thermochemical processes, indicating the potential of agricultural residues as renewable energy sources (Makaborang et al., 2020). The combined utilization of these materials therefore presents an opportunity not only to reduce agricultural waste but also to enhance briquette quality through complementary material properties.

Previous studies have demonstrated that particle size, binder ratio, raw material composition, and torrefaction conditions significantly influence the physical, thermal, and mechanical properties of biomass briquettes, including density, durability, and calorific value (Abineno et al., 2024; Dethan JJS et al., 2024). According to Kette et al. (2024), the addition of adhesive significantly affects the physical and mechanical properties of waste-based briquettes, indicating that binder composition plays a crucial role in densification and strength outcomes.

The use of semi-empirical regression models has further been shown to provide reliable predictions of briquette properties when grounded in physical interpretation (Dethan, 2024a, 2024b). However, several studies have focused on optimizing individual processing parameters through experimental comparison; predictive modeling approaches that explicitly link formulation parameters to briquette performance remain limited (Bunga et al., 2024; Dethan, 2024b).

From a materials and mechanical perspective, briquette performance is strongly influenced by densification behavior and interparticle interactions. Density plays a central role in determining mechanical strength, as increased particle packing reduces internal voids and enhances load transfer through interparticle contacts. Despite this understanding, relatively few studies have integrated mixture composition, densification behavior, and mechanical performance into a unified predictive framework. Therefore, this study aims to develop an integrated semi-empirical predictive model that links mixture ratio, densification behavior, and compressive strength of biomass briquettes produced from candlenut shell and tamarind peel.

MATERIALS AND METHODS

Materials

The raw materials used in this study consisted of candlenut shell and tamarind peel, which were collected from agricultural waste sources in Posiwatu Village, Wulandoni District, Lembata Regency, Indonesia.

The candlenut shells were collected in whole-shell form after nut removal, while tamarind peels were collected as dried outer fruit pericarps. Both materials were initially in coarse, irregular shapes and were not pre-shredded prior to collection. The raw materials were air-dried to reduce surface moisture before carbonization. Initial moisture content of the raw materials was approximately 12–15% (wet basis) prior to carbonization. After drying, the materials were subjected to carbonization under limited oxygen conditions to produce charcoal suitable for grinding and briquetting.

Equipment

The main equipment employed in this study included a carbonization unit, mechanical grinder, 40-mesh sieve, hydraulic briquette press, compressive strength testing apparatus, analytical balance, and drying facilities for moisture reduction (Figure 1). All measurements were conducted using calibrated instruments to ensure data reliability.

Experimental design

The experiment was designed using a completely randomized design (CRD) with five different mixture ratios of candlenut shell charcoal to tamarind peel charcoal, namely 1:3, 1:2, 1:1, 2:1, and 3:1 (w/w). Each treatment was replicated three times, resulting in a total of 15 experimental units.

The effect of mixture ratio on briquette quality was evaluated through physical and mechanical parameters, namely moisture content, density, and compressive strength.

Briquette preparation procedure

The collected candlenut shells and tamarind peels were first cleaned and air-dried to reduce surface moisture. Carbonization was then carried out under limited oxygen conditions until charcoal was obtained.

Figure 1. Briquette production stages: (A) charcoal–binder mixture before compaction; B) cylindrical steel die (40 mm diameter); (C) briquette compaction under uniaxial loading using a 2-ton hydraulic press; (D) produced briquettes after drying

The resulting charcoal was ground using a mechanical grinding mill until fine powder was obtained. The ground material was then sieved through a 40-mesh sieve (≤ 0.425 mm) to ensure uniform particle size distribution. All particles used in briquette production passed completely through the 40-mesh screen. The use of uniform fine particles was intended to enhance packing efficiency and interparticle contact during compaction.

A binder solution was prepared by dissolving 10% (w/v) tapioca starch in water and heating until a homogeneous gel was formed. The binder was added at approximately 8% (dry basis) relative to the total mass of charcoal mixture. The combined mixture was thoroughly blended to ensure uniform binder distribution prior to compaction. After drying, the final moisture content of the briquettes ranged between 6.02% and 6.06%, as verified by oven-drying at 105 °C until constant mass.

The charcoal powders were mixed according to the specified ratios and blended with the starch gel using manual mechanical stirring in a stainless-steel mixing container for approximately 10 minutes until a homogeneous mixture was obtained. Mixing time and procedure were kept consistent for all treatments to ensure uniform binder distribution and comparable densification behavior.

The mixture was subsequently molded using a hydraulic press to form cylindrical briquettes. The briquettes were molded using a hydraulic press with a maximum capacity of 2 tons. The forming die produced cylindrical briquettes with a diameter of 40 mm and a height of approximately 50 mm. Based on the press capacity and briquette cross-sectional area, the estimated maximum compaction pressure applied during pressing was approximately 15.9 MPa. Each briquette was subjected to peak compaction load under uniaxial compression conditions before demolding.

The formed briquettes were dried under natural conditions for approximately seven days until a constant mass was achieved, indicating sufficient moisture removal. The dried briquettes were then stored in airtight containers prior to testing.

Determination of briquette properties

Moisture content

Moisture content was determined using the oven-drying method at 105 °C until constant mass was achieved, following standard gravimetric procedures for solid biofuels. After natural drying, all briquettes were conditioned under laboratory ambient conditions (25 ± 2 °C) prior to testing to ensure equilibrium moisture content (ISO17225-1, 2021). The final moisture values therefore represent controlled equilibrium moisture rather than uncontrolled natural drying variations.

Density

Briquette density (p) was calculated by dividing the mass of the briquette by its volume, as shown in Equation 1:

$$\rho = \frac{m}{v} \tag{1}$$

where: m is the mass (g) and v is the volume (cm^3) of the briquette.

Compressive strength

Compressive strength was measured using a hydraulic compression testing device under uniaxial loading conditions. Each briquette was placed between two parallel steel plates and loaded axially until structural failure occurred. The maximum load recorded at the point of fracture was defined as the peak compressive strength. The reported values therefore represent the maximum stress required to cause briquette shattering, as shown in Equation 2.

$$\sigma_c = \frac{F}{A} \tag{2}$$

where: F is the maximum load at failure (N) and A is the cross-sectional area of the briquette (cm^2).

Development of predictive models

To enhance the interpretability and applicability of the experimental results, empirical and semi-empirical predictive models were developed to describe the relationship between mixture ratio, density, and compressive strength of the briquettes.

Because moisture content exhibited minimal variation across treatments (approximately 6%), it was not included as an independent variable in the main modeling framework. The modeling approach focused on densification behavior and mechanical integrity.

Mixture ratio–density model

The relationship between mixture ratio (R) and briquette density (ρ) was described using a quadratic empirical model, as shown in Equation 3:

$$\rho = aR^2 + bR + c \tag{3}$$

This form was selected to represent the presence of an optimal densification condition resulting from the balance between rigid carbonaceous particles and natural binding components.

Density–compressive strength model

The relationship between briquette density and compressive strength was modeled using linear regression, as shown in Equation 4:

$$\sigma_c = \alpha\rho + \beta \tag{4}$$

This model assumes that mechanical performance is primarily governed by packing efficiency and the solid load-bearing fraction within the briquette structure.

Integrated semi-empirical model

By combining the two relationships, a semi-empirical integrated model was formulated to predict compressive strength as a function of mixture ratio, as shown in Equation 5:

$$\sigma_c = \alpha\,(aR^2 + bR + c) + \beta \tag{5}$$

This integrated model provides a practical predictive tool for briquette formulation optimization.

Model evaluation and statistical analysis

Model performance was evaluated using the coefficient of determination (R^2) and visual comparison between predicted and experimental values. Experimental data were statistically analyzed using analysis of variance (ANOVA) at a 95% confidence level (α = 0.05), followed by Duncan's Multiple Range Test (DMRT) to identify significant differences among treatments.

Regression analysis was performed to estimate model coefficients and assess goodness of fit.

RESULTS AND DISCUSSION

Experimental results of briquette properties

The experimental results of briquette characterization are presented in Table 1, including moisture content, density, and compressive strength for each mixture ratio of candlenut shell charcoal and tamarind peel charcoal.

As shown in Table 1, the moisture content of all briquette samples ranged from 6.02% to 6.06%. These values were determined using the oven-drying method at 105 °C until constant mass and represent equilibrium moisture conditions after controlled drying. According to international solid biofuel standards (ISO 17225), moisture content below 10% is recommended to ensure stable combustion, reduced emissions, and improved storage stability. Therefore, all briquettes produced in this study satisfy international moisture requirements for solid biofuels.

In contrast, density exhibited substantial variation as a function of mixture ratio. Briquette density increased with increasing proportion of

Table 1. Physical and mechanical properties of briquettes at different mixture ratios

Mixture ratio (candlenut shell: tamarind peel)	Moisture content (%)	Density (g/cm³)	Compressive strength (MPa)
1:3	6.04 ± 0.03^{b}	0.99 ± 0.31^{cd}	2.22 ± 0.15^{bc}
1:2	6.02 ± 0.00^{ab}	1.28 ± 0.50^{bc}	2.35 ± 0.35^{bc}
1:1	6.05 ± 0.00^{ab}	1.86 ± 0.36^{a}	2.91 ± 0.25^{a}
2:1	6.05 ± 0.00^{ab}	1.60 ± 0.18^{ab}	2.48 ± 0.31^{ab}
3:1	6.06 ± 0.02^{a}	0.70 ± 0.27^{d}	1.99 ± 0.37^{c}

Note: Values are presented as mean ± standard deviation (n = 3).

candlenut shell charcoal up to the 1:1 ratio, at which the highest mean density (1.86 g/cm³) was obtained. Beyond this ratio, density decreased markedly, particularly at the 3:1 ratio, which showed the lowest mean density (0.70 g/cm³). This behavior suggests that mixture ratio strongly influences particle packing efficiency and internal void structure within the briquettes.

A similar trend was observed for compressive strength, which increased with density and reached its maximum value (2.91 MPa) at the 1:1 mixture ratio. Briquettes produced with either lower or higher proportions of candlenut shell exhibited reduced compressive strength. This pattern indicates that mechanical performance is closely linked to structural compaction and interparticle contact, which are optimized at intermediate mixture ratios.

The relatively larger standard deviations observed for density and compressive strength, compared to moisture content, reflect the sensitivity of these properties to material heterogeneity and packing behavior. Such variability is commonly reported in biomass briquettes produced from agricultural residues and is associated with differences in particle shape, size distribution, and bonding efficiency (Malovanyy et al., 2023).

Overall, the experimental results demonstrate that while moisture content remained relatively stable across treatments, density and compressive strength were strongly governed by mixture ratio. The concurrent maximization of density and compressive strength at the 1:1 ratio indicates the presence of an optimal composition that balances rigid carbonaceous particles from candlenut shell charcoal with the binding contribution of tamarind peel. These findings provide a robust experimental foundation for subsequent mechanistic interpretation and predictive modeling, as discussed in the following sections.

Moisture content and its limited role in mechanical performance

Moisture content is a critical parameter in biomass briquettes because it can influence ignition behavior, combustion efficiency, and mechanical stability. However, as shown in Table 1, the moisture content of all briquette samples in this study was confined to a very narrow range, between 6.02% and 6.06%, with extremely low standard deviations across mixture ratios.

Although statistical analysis detected significant differences among treatments ($p < 0.05$), the absolute variation in moisture content was minimal (≤0.04%). From a practical and mechanical standpoint, such a small difference is unlikely to produce a measurable impact on briquette strength or structural integrity. All samples satisfied commonly recommended moisture limits for biomass briquettes, which are generally below 10% to ensure stable combustion and prevent biological degradation during storage (Obi et al., 2022; Saeed et al., 2021).

The low variability in moisture content can be attributed to the uniform drying procedure, consistent binder concentration, and similar processing conditions applied across all treatments. This uniformity suggests that moisture was effectively controlled during briquette production and did not act as a governing factor differentiating the mechanical behavior of the samples.

In contrast, density and compressive strength exhibited substantially greater variation among mixture ratios. This disparity indicates that mechanical performance was primarily governed by structural factors, such as particle packing efficiency, interparticle contact, and void fraction, rather than by moisture content. Similar observations have been reported in previous studies, where moisture content influenced briquette performance only when large variations were present, while density remained the dominant parameter controlling mechanical strength within narrow moisture ranges (Ngangyo Heya et al., 2022; Obi et al., 2022).

Based on these considerations, moisture content was excluded from the primary predictive modeling framework developed in this study. This decision allows the analysis to focus on the dominant mechanisms controlling briquette strength, namely densification behavior and interparticle load transfer. The approach is consistent with modeling strategies commonly adopted in biomass briquette research, where parameters with limited variability are treated as controlled conditions rather than independent predictors.

Effect of mixture ratio on briquette density

The effect of mixture ratio on briquette density is presented in Figure 2a and Figure 2b. Figure 2a shows the quadratic regression model describing the relationship between mixture ratio and briquette density, while Figure 2b presents the residual distribution used to evaluate the adequacy of the model.

As shown in Figure 2a, briquette density does not increase monotonically with increasing candlenut shell proportion. Instead, density initially increases from the 1:3 ratio to the 1:1 ratio, where the highest mean density is achieved, and subsequently decreases at higher ratios (2:1 and 3:1). This unimodal trend indicates that densification behavior is governed by a balance between material composition and packing efficiency rather than by carbon content alone.

The non-linear dependence illustrated by the quadratic fit in Figure 2a suggests the existence of an optimal densification condition. At lower candlenut shell fractions, the higher proportion of tamarind peel contributes to particle binding but limits the effective rigid carbon fraction, resulting in moderate density. As the mixture approaches the 1:1 ratio, an optimal combination of rigid carbonaceous particles and sufficient binding components promotes efficient particle rearrangement, reduced void fraction, and improved packing during compaction.

At higher candlenut shell proportions, the decline in density can be attributed to the dominance of rigid charcoal particles combined with insufficient binding material. This condition reduces interparticle cohesion, increases internal voids, and limits effective load transfer during pressing, leading to lower final density. Similar non-linear density trends have been reported for biomass briquettes produced from various agricultural residues, where excessive rigid particle content leads to poor packing efficiency despite higher carbon availability.

The adequacy of the quadratic model is further supported by the residual distribution shown in Figure 2b. The residuals are randomly scattered around zero without any systematic pattern, indicating that the quadratic regression provides an unbiased representation of the experimental density data within the investigated mixture ratio range.

Modeling of density as a function of mixture ratio

Based on the non-linear trend observed in the experimental data (Figure 2a), a quadratic regression model was adopted to describe the relationship between mixture ratio and briquette density. The selection of a quadratic form is justified by the unimodal behavior of the data, which cannot be adequately represented by a linear model and indicates the presence of an optimal densification condition.

The fitted quadratic model (Figure 2a) is expressed, as shown in Equation 6:

$$\rho = -0.55R^2 + 1.68R + 0.57;\ R = 0.94 \quad (6)$$

The high coefficient of determination indicates that approximately 92% of the variation in briquette density is explained by the mixture ratio, confirming that composition is the dominant factor controlling densification behavior under the applied processing conditions.

The negative quadratic coefficient confirms the concave-downward shape of the curve and provides mathematical evidence for the existence of an optimal mixture ratio. The optimal ratio corresponding to maximum density was obtained from the first derivative of the model, as shown in Equation 7:

$$\frac{d\rho}{dR} = 2aR + b = 0 \quad (7)$$

which yields an optimal ratio of approximately R≈1–1.5. This predicted optimum lies within the experimentally investigated range and is consistent with the highest density observed experimentally at the 1:1 mixture ratio, indicating good agreement between model prediction and experimental observation.

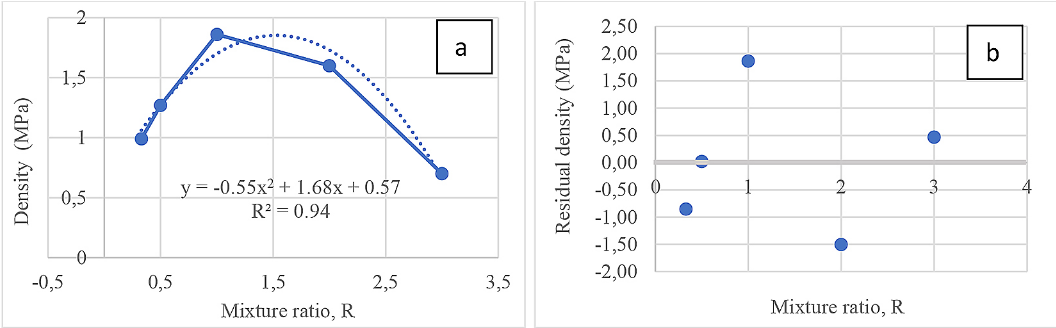

Figure 2. (a) Quadratic regression model describing the relationship between mixture ratio and briquette density; (b) residual distribution of the quadratic density model

From a mechanistic standpoint, the quadratic behavior reflects the competing effects of material composition on packing efficiency. At lower ratios, the higher proportion of tamarind peel contributes to binding but limits the rigid carbon fraction, while at higher ratios the dominance of rigid candlenut shell charcoal reduces interparticle cohesion due to insufficient binding components. At intermediate ratios, these effects are balanced, resulting in reduced void fraction and enhanced particle packing.

The adequacy of the quadratic model is further supported by the residual analysis shown in Figure 2b. The residuals are randomly distributed around zero without any systematic pattern, indicating that the model is unbiased and that no higher-order or alternative functional form is required within the investigated range.

Effect of density on compressive strength

The relationship between briquette density and compressive strength is presented in Figure 3. A clear positive and nearly linear trend is observed, indicating that briquettes with higher density exhibit greater mechanical resistance to compressive loading.

As shown in Figure 3, compressive strength increases consistently with increasing density across the investigated range. Briquettes with lower density display reduced strength, whereas those with higher density – particularly those produced near the optimal mixture ratio – exhibit markedly improved mechanical performance. This trend highlights density as a primary controlling parameter for compressive strength.

From a mechanistic perspective, the observed linear dependence is consistent with granular material mechanics, where compressive strength is governed by the number and continuity of interparticle contacts. As density increases, internal voids are reduced, particle contact area increases, and load transfer pathways become more effective, resulting in enhanced resistance to mechanical failure. Previous studies on biomass briquettes and pellets have shown that densification plays a critical role in improving thermal efficiency and combustion performance, as increased density enhances fuel handling, combustion stability, and overall energy conversion efficiency (Rohmah et al., 2026). Similar relationships between densification behavior and mechanical or energetic performance have been reported for briquettes derived from kesambi biomass and other agricultural residues (Abineno et al., 2024; Cabrales et al., 2020; Dethan et al., 2024).

The slope of the linear model represents the sensitivity of compressive strength to densification, reflecting how efficiently increased packing translates into mechanical strength. Meanwhile, the intercept represents the baseline structural integrity of the briquette system under the applied processing conditions, including binder content, compaction pressure, and particle characteristics. Importantly, no evidence of saturation or non-linear strengthening behavior was observed within the investigated density range, justifying the use of a linear model.

Integrated predictive model for briquette strength

To establish a direct link between mixture composition and mechanical performance, the density-based quadratic model was coupled with the linear density–strength relationship to form an integrated semi-empirical predictive model.

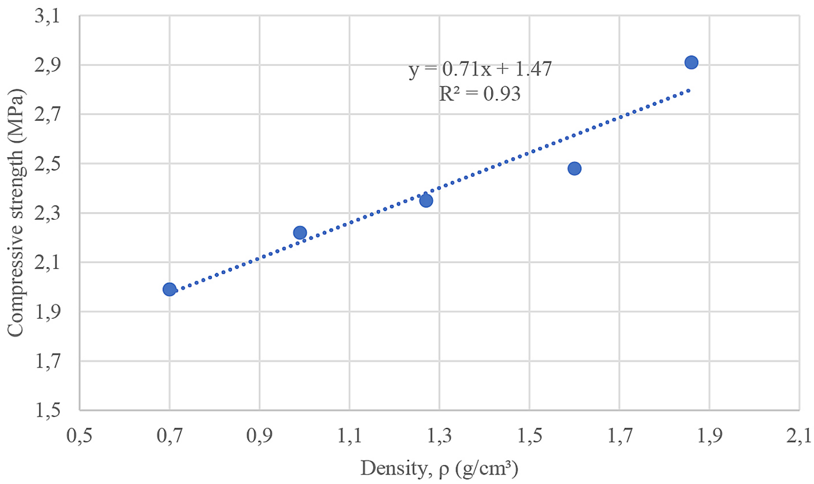

Figure 3. The relationship between briquette density and compressive strength

This framework reflects the causal chain observed experimentally, where mixture ratio governs densification behavior, and densification, in turn, controls compressive strength.

By combining the two regression relationships, compressive strength can be expressed directly as a function of mixture ratio (R), as shown in Equation 8:

$$\sigma_c = 0.71\begin{pmatrix}-0.55R^2 + \\ 1.68R + 0.57\end{pmatrix} + 1.47 \quad (8)$$

This expression can be algebraically simplified to yield Equation 9:

$$\sigma_c = -0.39R^2 + 1.19R + 1.82 \quad (9)$$

The resulting integrated model exhibits a concave-downward quadratic form, indicating the presence of an optimal mixture ratio that maximizes compressive strength. This behavior mirrors the density optimum identified experimentally and confirms that mechanical performance is indirectly governed by mixture composition through densification efficiency.

The predicted optimal region derived from the integrated model lies within the experimentally investigated range and is consistent with the highest compressive strength observed at the 1:1 mixture ratio. Minor deviations between predicted and experimental values are attributed to experimental variability and the discrete nature of the tested ratios, highlighting the model's role as a predictive and interpretative tool rather than an absolute descriptor.

From a practical standpoint, the integrated model enables preliminary formulation design by estimating mechanical performance without extensive trial-and-error experimentation. From a mechanistic perspective, it demonstrates that optimal briquette strength is achieved by balancing rigid carbonaceous particles and binding components to maximize packing density and interparticle load transfer.

CONCLUSIONS

This study demonstrated that the mixture ratio of candlenut shell charcoal and tamarind peel significantly influences the structural and mechanical properties of biomass briquettes. Moisture content remained stable across treatments and did not contribute significantly to mechanical variation.

Briquette density exhibited a non-linear dependence on mixture ratio, with a maximum observed near the 1:1 ratio. Compressive strength showed a strong linear relationship with density, confirming that mechanical performance is primarily governed by densification efficiency and interparticle load transfer.

The integrated semi-empirical model successfully linked mixture ratio, density, and compressive strength, accurately reproducing the experimental trends and identifying an optimal composition consistent with the highest measured strength. The results confirm density as the key intermediate parameter connecting formulation and mechanical performance in biomass briquettes derived from agricultural residues.

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