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Energy content analysis of extruded briquettes: effects of mesh granularity and corn cob-to-coconut shell residue blend composition

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Abstract

The conversion of agricultural residues into biomass briquettes presents a sustainable alternative for energy generation, addressing waste management challenges, reducing fossil fuel dependence, and mitigating carbon emissions. This study analyzes the influence of material mesh granularity and corn cob-to-coconut shell residue blend composition on the energy content and quality metrics of extruded briquettes. The primary objective is to investigate the effects of formulation parameters on energy yield (calorific value), structural durability (shatter index), and ash content. Employing an experimental approach combined with statistical analysis (Analysis of Variance (ANOVA) and Friedman test), the impacts of varying mesh sizes and compositional mass ratios were systematically evaluated. The results showed that calorific values ranged between 4,739–5,143 cal/g, ash content varied from 14.95–23.62%, and the shatter index from 0.04–1.33%. The optimal performance was obtained at 50 mesh with 70% corn cob charcoal and 30% coconut shell residue, yielding the highest calorific value (5,143 cal/g), the lowest ash content (16.66%), and excellent durability (shatter index 0.04%). Statistical analysis (ANOVA and Friedman test) confirmed that both particle size and blending ratio significantly affected all quality metrics ($p < 0.05$). These findings provide actionable insights for enhancing energy content and overall quality of extrusion-derived briquettes from agricultural residues. The research underscores the essential role of precise material selection and parameter control in developing efficient and sustainable solid biomass fuels.

Keywords:
Energy content analysis, biomass briquettes, mesh granularity, blend composition, extrusion process.

1 Introduction

The production of biomass briquettes has emerged as a promising approach for addressing energy demands while promoting environmental sustainability, especially in regions rich in agricultural residues like Indonesia. Biomass briquettes, typically produced from organic residues such as corn cobs and coconut shells, serve as an alternative fuel source to traditional fossil fuels [1]. Indonesia ranks among the top five global corn producers, generating approximately 19-21 million tons of corn annually. It is estimated that about 20% of the harvested corn weight consists of cobs, which translates into roughly 2.9-4.2 million tons of corn cobs available each year as agricultural residue [2]. Similarly, Indonesia is the world's largest coconut producer, with annual production exceeding 16 million tons of coconuts. From this, around 30% of the total fruit weight is shell, yielding nearly 4.8-5.0 million tons of coconut shell residue per year [3]. These figures demonstrate that both corn cobs and coconut shells represent abundant biomass feedstock's, which, if properly utilized, can be converted into high-energy briquettes to substitute fossil fuels and reduce waste accumulation [4].

This aligns with the growing emphasis on sustainable energy solutions and waste management in many parts of the world. The conversion of agricultural waste into briquettes mitigates waste disposal challenges and provides a viable energy source, thereby reducing dependence on fossil fuels and contributing to lower carbon emissions [4].

The quality of biomass briquettes is complexly governed by the multidimensional interaction of various material and process factors. The raw biomass type dictates intrinsic properties such as lignin, cellulose, and hemicellulose content, which influence calorific value and binding characteristics [3]. The selection of binder (adhesive) and its concentration critically affects mechanical integrity and particulate emissions [4]. Pre-treatment thermochemical parameters, including pyrolysis temperature, heating rate, and residence time, significantly alter charcoal chemical composition and energy density [5]. The torrefaction process (heating at 200–300°C under inert atmosphere) enhances hydrophobic properties and calorific value but impacts feedstock grind-ability [6]. During the densification stage, compression pressure, dwell time, die temperature, and moisture content exert dominant influences on compact density and impact resistance (shatter index) [7], [8].

The blend composition and mesh granularity are also two critical factors that directly influence the quality of biomass briquettes. These factors determine the briquette's physical, chemical, and mechanical characteristics, which are essential for ensuring high energy output, low emissions, and user-friendly handling and storage [9]. The selection of mesh granularity levels was based on their relevance to biomass densification processes. Finer particles generally enhance briquette density and mechanical integrity by reducing inter-particle voids, whereas coarser particles may limit compaction efficiency. Evaluating multiple mesh sizes allows identification of an optimal balance between grinding energy requirements and briquette quality.

Similarly, the blending ratios of corn cob to coconut shell charcoal were designed to investigate potential synergistic effects between the two materials. Coconut shell charcoal contributes higher hardness and fixed carbon content, while corn cob charcoal offers improved reactivity and combustion characteristics. By systematically varying the blending ratio, this study aims to determine the optimal combination that maximizes energy content while maintaining acceptable ash content and mechanical durability. Research in this domain has primarily focused on optimizing these parameters to enhance briquette quality and performance.

The blend composition, or the ratio of different biomass materials, plays a crucial role in determining the properties of the final briquette [10]. Corn cobs and coconut shells are two commonly used materials due to their widespread availability and energy-rich properties. According to a study by Sabo et al. [11], different compositions of these materials result in variations in density, calorific value, and ash content. Higher ratios of coconut shells tend to increase the calorific value due to their high lignin content, which enhances energy release during combustion. Conversely, corn cobs contribute to a higher ash content, which can affect briquette stability and reduce overall energy output. Researchers have found that a blend of 75% corn cobs and 25% coconut shells yields an optimal balance between calorific value and ash content source [11].

Moreover, the blend ratio affects not only the combustion properties but also the structural integrity of the briquettes. A higher percentage of coconut shells enhances the compressive strength of the briquettes, making them less prone to breakage during transportation and handling. Conversely, a higher corn cob content may improve combustion rates but may compromise durability due to lower density [11].

Mesh granularity is another vital parameter in biomass briquette production. The granularity of the biomass material determines the porosity and surface area, which subsequently affect combustion characteristics and briquette density. Research by Dziedzic et al. [12] indicates that finer particles contribute to a more uniform density and stronger structural integrity due to reduced void spaces within the briquette matrix source. However, there is a trade-off, as very fine particles can lead to increased production costs due to higher energy requirements for grinding [13].

Optimizing mesh size is thus essential for achieving desirable briquette properties. Smaller mesh granularity increases the compactness and reduces the tendency of the briquettes to disintegrate. Additionally, finer particles promote uniform heat distribution during combustion, which enhances energy efficiency [14]. Studies have highlighted that a mesh granularity within the range of 2-3 mm offers a balanced combination of durability and combustion efficiency for biomass briquettes derived from coconut shells and corn cob sources.

The extrusion process is commonly employed to form briquettes due to its ability to produce high-density, uniform briquettes with minimal binder usage [15]. Extrusion applies mechanical pressure to compact the biomass particles, thus improving durability and combustion properties. According to [16], extrusion enhances briquette stability by eliminating moisture content, which further enhances calorific output.

In this study, two distinct types of agricultural waste were utilized, i.e. corn cobs and charcoal residue derived from coconut shells. The charcoal residue results from the carbonization process of coconut shells at temperatures between 600°C and 700°C, lasting approximately 3-4 hours until they are fully converted into charcoal. Following this, a screening process is conducted, sieving the charcoal to a 2 mm size to separate pure charcoal from charcoal residue. Pure charcoal is typically used for shisha briquettes. The remaining charcoal residue is sent to briquette manufacturing facilities, where it undergoes further screening at a 1 mm size to produce two types of charcoal residue. The first type consists of cleaner charcoal residue mixed with a small amount of ash and is commonly used for BBQ briquettes. The second type, characterized by a dirtier residue with traces of soil and sand, is often utilized as a fertilizer additive. In this study, the first type of charcoal residue, intended for use in BBQ briquettes, is selected as a raw material mixture.

This research employs an integrated experimental-statistical approach to systematically evaluate the impact of mesh granularity and compositional ratios between corn cobs and charcoal residue on briquette performance metrics (i.e. calorivic value, ash content, and shatter index). By evaluating these factors, the research seeks to optimize briquette blends to enhance both energy efficiency and structural resilience, thereby offering insights into the effective utilization of agricultural waste in sustainable fuel production and reduce reliance on fossil fuels.

2 Research methods

To quantify parameter impacts, experimental methods and statistical analysis were integrated to investigate mesh granularity and compositional ratio effects on briquette calorific value, ash content, and shatter index.

The experimental phase involved preparing briquette samples with different mesh sizes and blending compositions of corn cob and coconut shell residues. These samples were then subjected to a series of standardized tests to measure key performance indicators, including calorific value, ash content, and shatter index. The shatter index or drop test is a standard method for evaluating the durability and impact resistance of briquettes, pellets, or other agglomerated materials, particularly in industries where solid fuel materials are commonly handled.

The calorific value was measured with a bomb calorimeter to determine the energy content of each sample, while ash content was obtained by incinerating the samples at controlled temperatures and calculating the percentage of residual ash. To measure durability and resistance to breakage, the shatter index test involved dropping each briquette from a set height. This test assesses how well a briquette can withstand mechanical handling and transport without significant breakage or degradation.

Following data collection from these tests, we applied statistical techniques (ANOVA) and the Friedman test to assess the significance of variations in mesh size and compositional ratios on each performance metric. ANOVA and Friedman tests were applied to assess whether differences in calorific value, ash content, and shatter index were statistically significant across different mesh granularities and composition ratios, allowing us to identify the factors that most strongly influence briquette quality. These analyses enabled us to identify the optimal formulations that maximize energy output, structural durability, and the overall quality of the briquettes as a fuel source.

This methodological approach offered an in-depth understanding of how mesh granularity and composition affect biomass briquette performance, supporting the development of efficient and sustainable fuel alternatives.

2.1 Biomass pretreatment

The corn cobs used as raw materials for briquette production were sourced from corn farmers in Tuban Regency, East Java. The cobs were sun-dried for three days, with an exposure of nine hours each day, to reduce their moisture content. The corn cobs were carbonized in a closed metal drum with limited oxygen at 450-500°C for 2 hours, and then cooled naturally for 8-10 hours to ambient temperature. Coconut shells were carbonized separately at 600-700°C for 3-4 hours and cooled under the same conditions.

This drying process resulted in corn cobs with a pale yellow color and lighter weight, indicating low moisture levels. After drying, the corn cobs underwent a carbonization process, which was carried out over two hours to convert the cobs into charcoal. Once carbonized, the corn cob charcoal was allowed to cool before being processed further.

The cooled charcoal was then chopped using a shredding machine to obtain smaller mesh granularity. The shredded briquette material was ground using an FFC23 disk mill machine produced by PT. Karya Delitama, Indonesia (Fig. 1), which refined the charcoal into finer granules. Mesh Granularity (MG) levels, i.e. 20 mesh (≤850 μm), 40 mesh (≤420 μm), and 50 mesh (≤297 μm), were defined using standardized metal wire cloth test sieves in accordance with ISO 3310-1:2016 [17]. These categories were chosen to represent coarse, medium, and fine particles, respectively. Such classification is commonly applied in biomass briquette studies to balance grinding energy requirements with briquette density and combustion performance. This size differentiation allows for precise control over the final briquette structure, which is critical for achieving optimal briquette performance characteristics.

Fig. 1. FFC23 disk mill machine.

2.2 Briquette production

The production process begins after the raw materials, corn cob charcoal and coconut shell residue charcoal, are refined to the desired mesh size. Briquette dough is then prepared by combining these raw materials with tapioca flour and water, which serve as binding agents. Each batch for experimentation is prepared to weigh 3 kg, comprising 2.85 kg of charcoal mixture from corn cob and coconut shell residue, with an adhesive ratio of 5% (0.15 kg of tapioca flour). Additionally, 1 liter of water is added to the mixture. For composition A (30% corn cob charcoal, 70% coconut shell residue), the formulation contained 0.855 kg corn cob charcoal and 1.995 kg coconut shell residue. For composition B (50:50), 1.425 kg corn cob charcoal and 1.425 kg coconut shell residue. For composition C (70:30), 1.995 kg of corn cob charcoal and 0.855 kg coconut shell residue. Tapioca starch at 5% was selected as the binder because it provides adequate binding strength and durability while minimizing smoke and ash formation. Ratios above 5% can reduce calorific value, whereas lower concentrations risk poor mechanical integrity. Hot water at approximately 60°C was used to gelatinize tapioca starch before mixing with charcoal powder. This improves binder distribution and bonding within the briquette dough. Each component was weighed using a calibrated digital balance (±0.01 g accuracy) prior to mixing. The weighed materials were manually homogenized for approximately 15 minutes to ensure uniform distribution before binder addition (Fig. 2).

Fig. 2. Briquette extruder machine.

The briquette formation in this study utilizes an extruder machine powered by a 16 HP diesel engine (Jiang fa, China). Inside the extruder, a screw mechanism serves to mix and compress the briquette dough, while a square outlet at the end shapes the briquettes as they are extruded. The screw is rotated via a v-belt transmission, with speed reduction managed by an 80-type gearbox with a 1:60 ratio. The extruder screw operated at approximately 120 rpm (after gearbox reduction), generating an extrusion pressure of 8-10 MPa at the die outlet, which ensured uniform density and continuous extrusion. The extruded briquettes were cut into cuboid shapes measuring 2.5×2.5×5 cm as illustrated in Fig. 3. This mechanical process ensures consistent briquette dimensions and density, facilitating subsequent analyses of briquette quality.

Fig. 3. Briquette final product.

2.3 Experimental design

This research investigates two key parameters in the briquette production process, i.e. MG and Blend Composition (BC). The mesh sizes were selected to represent coarse, medium, and fine particle sizes commonly used in briquette studies (20, 40, 50 mesh respectively). This range allows analysis of grinding energy cost versus briquette density and combustion efficiency.

This variation in particle fineness significantly influences the compaction behavior of raw materials and the development of pore structures during extrusion. The BC was defined as the percentage ratio of corn cob charcoal to coconut shell residue charcoal. For analytical purposes, the BC was categorized into three groups: composition A (30% corn cob charcoal, 70% coconut shell residue), composition B (50% corn cob charcoal, 50% coconut shell residue), and composition C (70% corn cob charcoal, 30% coconut shell residue).

To avoid confusion, all samples were coded as MG–BC. For example, 20-A refers to 20 mesh with composition A (30% corn cob, 70% coconut shell residue), 40-B refers to 40 mesh with composition B (50:50), and 50-C refers to 50 mesh with composition C (70% corn cob, 30% shell). This coding ensures consistency in presenting the results. The values corresponding to these variations are summarized in Table 1, providing a systematic framework for analyzing the effects of particle size and blending ratio on briquette quality. This methodological approach offers important insights into the optimization of biomass briquette formulations.

Table 1. Parameter settings

Parameter	Symbol	Unit	Level		
			1	2	3
Mesh granularity	MG	mesh	20	40	50
Blend composition	BC	-	A	B	C

For each experimental condition (mesh granularity × blending composition), three independent briquette samples were prepared as replicates. Homogeneity was ensured through controlled mixing procedures until a consistent texture was obtained. Moisture content was controlled by drying the raw materials prior to carbonization and by maintaining a fixed water addition during binder preparation, ensuring comparable feedstock conditions for all samples.

To evaluate the quality of the produced briquettes, a series of standardized thermal, physical, and mechanical tests were conducted. The briquette quality assessment includes tests for calorific value, ash content, and shatter index. The calorific value was measured using a Parr 6200 Isoperibol Calorimeter (Parr Instrument Company, USA), following the ASTM D 5865-13 standard for determining the gross calorific value of coal and coke [18]. Ash content analysis was performed in accordance with ASTM D3174-12 [19], which specifies the method for determining ash content in analytical samples of coal and coal-derived coke, using a muffle furnace manufactured by PT Hade Pertama Electric, Indonesia. Briquette durability (shatter index) was determined using a drop test to evaluate mechanical strength and impact resistance. The test was conducted in accordance with ASTM D440-86 (R02), “Standard Test Method for Drop Shatter Test for Coal” [20], using a standard drop apparatus fabricated locally at University of Trunojoyo Madura. The procedure involves dropping the briquettes from a height of 1.8 meters onto a flat, even surface to evaluate their durability. Statistical analysis is applied to determine the significance of each parameter’s effect, using ANOVA for parametric data and the Friedman test for non-parametric data.

3 Results and discussion

3.1 Data collection

This study's briquette quality testing encompasses measurements of Calorific Value (CV), Ash Content (AC), and Shatter Index (SI). Each test was repeated three times, with the average values subsequently calculated. To reflect data variability, all experimental results are presented as mean values with standard deviation obtained from three replicates. Table 2 provides the mean values ± standard deviation for CV (cal/g), AC (%), and SI (%) for each treatment variation.

Table 2. Data collection

Code	CV (cal/gr)	AC (%)	SI (%)
20-A	4,739 ± 22	23.62 ± 0.58	0.36 ± 0.03
20-B	4,853 ± 26	23.29 ± 0.61	1.33 ± 0.11
20-C	4,992 ± 24	19.29 ± 0.47	0.16 ± 0.02
40-A	4,935 ± 21	22.60 ± 0.55	0.35 ± 0.03
40-B	5,109 ± 19	18.62 ± 0.42	0.44 ± 0.04
40-C	5,131 ± 17	14.95 ± 0.36	0.10 ± 0.01
50-A	4,888 ± 23	20.66 ± 0.49	0.05 ± 0.01
50-B	5,027 ± 20	19.29 ± 0.44	0.20 ± 0.02
50-C	5,143 ± 18	16.66 ± 0.40	0.04 ± 0.01

According to Table 2, the highest calorific value observed was 5,143 ± 18 cal/g, achieved with a 50-mesh granularity and a blend composition labeled as C (50-C), comprising 70% corn cob charcoal and 30% coconut shell residue. In contrast, the lowest calorific value, 4,739 ± 22 cal/g, was recorded for the 20-mesh granularity with composition A (20-A), which includes 30% corn cob charcoal and 70% coconut shell residue. The Indonesian Standard SNI 1-6235-2000 requires a calorific value of more than 5,000 cal/g. This criterion is satisfied by four out of the nine experimental combinations, indicating partial adherence to the SNI calorific value standard [21].

For ash content, the lowest value was 14.95 ± 0.36%, attained with a 40-mesh granularity and composition C (70% corn cob charcoal and 30% coconut shell residue). The highest ash content, at 23.62 ± 0.58%, was associated with the 20-mesh granularity and composition A (30% corn cob charcoal and 70% coconut shell residue). These values exceed the SNI 1-6235-2000 standard, which stipulates ash content must be below 8%, indicating that none of the combinations met the SNI ash content requirement.

In terms of the shatter index, the lowest result was 0.04 ± 0.01%, found with a 50-mesh granularity and composition C (70% corn cob charcoal and 30% coconut shell residue). The highest shatter index, at 1.33 ± 0.11%, came from the 20-mesh granularity and composition B (50% corn cob charcoal and 50% coconut shell residue). All combinations produced shatter index values below the SNI 1-6235-2000 standard limit of 4%, demonstrating that all combinations met the SNI requirements for shatter index.

3.2 Data interpretation

The data in Table 2 illustrate the trend in the impact of mesh granularity and blend composition on CV, AC, and SI. Fig. 4 displays the trend in the relationship between blend composition and calorific value across different mesh granularities.

The data indicates that an increase in the percentage of corn cob charcoal in the blend composition (from A to C) correlates with a rise in calorific value, suggesting that corn cob charcoal is more effective than coconut shell residue charcoal in boosting calorific output. Additionally, as mesh granularity increases, resulting in smaller raw material particles, the calorific value generally rises across all composition variations. This trend is likely due to smaller particle sizes creating denser briquettes with reduced inter-particle spaces, which restricts moisture absorption. These findings are consistent with previous studies showing an inverse relationship between calorific value and moisture content, where higher moisture levels lead to lower calorific output as more energy is expended in evaporating water within the briquettes [21].

Fig. 5 depicts the trend in ash content relative to mesh granularity across various blend compositions. The data indicate that as mesh granularity increases, meaning the raw material particles become finer, ash content generally decreases. In contrast, within the blend composition, a higher percentage of corn cob charcoal leads to increased ash content, suggesting that corn cob charcoal generates more ash than coconut shell residue.

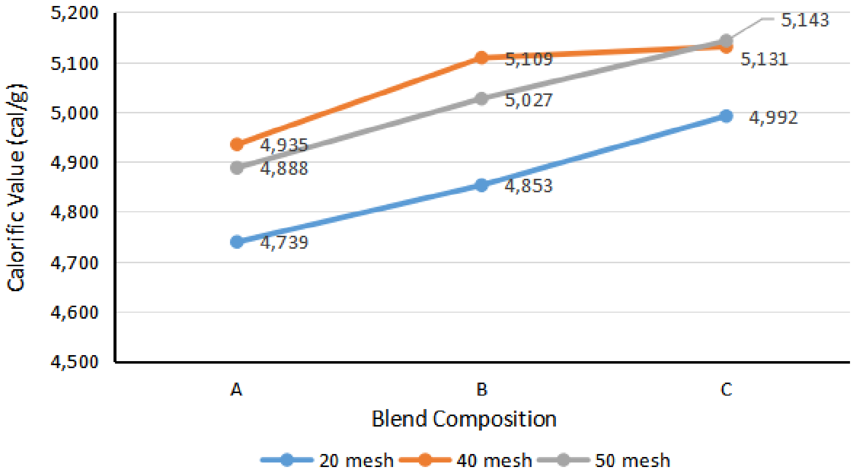

Fig. 4. Calorific value trend based on blend composition and mesh granularity.

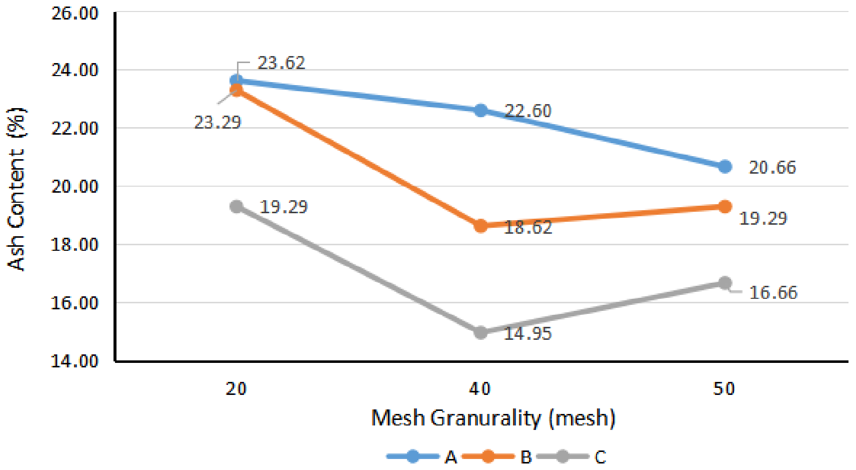

Fig. 5. Trend on ash content based on mesh granularity and blend composition.

Fig. 6 displays the shatter index, indicating that an increase in mesh granularity, corresponding to finer particle sizes, leads to a decrease in the shatter index. Furthermore, variations in the blend composition do not exhibit a clear trend, with the lowest shatter index occurring at the smallest proportion of corn cob charcoal in the composition.

Certain combinations exhibited comparatively lower performance. In particular, briquettes produced at coarser mesh granularity (20 mesh) showed reduced calorific value and higher shatter index, likely due to insufficient inter-particle bonding and higher internal void content. Similarly, compositions with higher proportions of coconut shell residue tended to exhibit increased ash content, which negatively affected the effective calorific value [22].

When compared with literature benchmarks, the calorific values obtained in this study (approximately 4,700–5,140 cal/g) are consistent with previously reported values for corn cob–based and coconut shell–based briquettes, which typically range from 4,600 to 5,300 cal/g depending on processing conditions and binder content [23], [24]. These results indicate that the optimal combination identified in this study performs comparably to, or better than, similar biomass briquettes reported in the literature, while meeting the quality requirements specified in SNI 01-6235-2000.

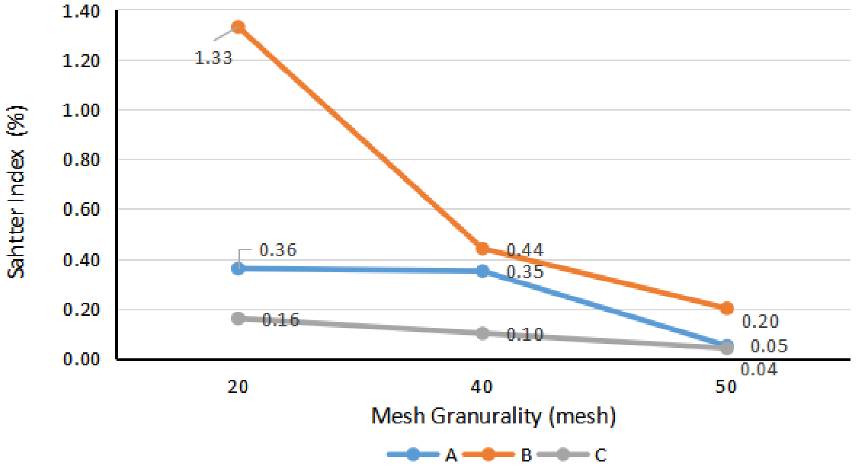

Fig. 6. Trend on shatter index based on mesh granularity and blend composition.

3.3 Statistical analysis

A statistical analysis was performed to determine the effect of research parameters on response variables. ANOVA was the primary statistical test used, with initial assumption testing, including normality and homogeneity tests, to confirm that the data were normally distributed and homogeneous. If data did not meet normality or homogeneity requirements, the Friedman test was used as an alternative. Following these assumption tests, it was found that CV and AC data were normally distributed and homogeneous, allowing ANOVA to be conducted. In contrast, the shatter index data did not exhibit normal distribution, so the Friedman test was applied.

This study employs the statistical hypotheses to evaluate parameter effects. The null hypothesis (H_0) states that variations in mesh granulatity and blend composition collectively exert no significant influence on briquette quality metrics, specifically calorific value, ash content, and shatter index. Conversely, the alternative hypothesis (H_1) contends that at least one variation in mesh granularity and/or blend composition significantly affects one or more of these response variables.

The ANOVA results for CV and AC are displayed in Tables 3 and 4, respectively, while Tables 5 and 6 present the Friedman test results for the SI. To assess the significance of a parameter's effect, the P-value is compared to the α level (0.05). If the P-value exceeds α, the null hypothesis (H_0) is accepted, indicating that the parameter setting does not have a significant impact on the response variable. However, if the P-value is less than α, the null hypothesis (H_0) is rejected, signifying that the parameter setting significantly influences the response variable.

According to Table 3, the P-values for both mesh granularity and blend composition are less than 0.05, indicating a significant effect on calorific value. Mesh granularity and blend composition contribute 42.65% and 54.78%, respectively.

Table 3. ANOVA for CV

Source	DF	Adj SS	Adj MS	F-value	P-value	% Contribution
MG	2	65,294	32,647.0	33.35	0.003	42.65
BC	2	83,853	41,926.3	42.83	0.002	54.78
Error	4	3,915	978.8			2.55
Total	8	153,062				

Similarly, in Table 4, the P-values for both mesh granularity and blend composition are less than 0.05, indicating that both factors significantly influence ash content. The contribution of blend composition (61.98%) is greater than that of mesh granularity (30.34%).

Table 4. ANOVA for AC

Source	DF	Adj SS	Adj MS	F-value	P-value	% Contribution
MG	2	21,418	10,709	7.91	0.041	30.34
BC	2	43,746	21,873	16.16	0.012	61.98
Error	4	5,415	1,354			7.67
Total	8	70,579				

Tables 5 and 6 reveal identical values for both mesh granularity and blend composition. Both tables also report a P-value below 0.05, indicating that mesh granularity and blend composition have a significant impact on the shatter index.

Table 5. Friedman test of SI for mesh granularity

DF	Chi-square	P-value
2	12.67	0.002

Table 6. Friedman test of SI for blend composition

DF	1	P-value
2	12.67	0.002

Based on the results, the statistical analysis robustly confirms that both mesh granularity and blend composition exert statistically significant influences ($p < 0.05$) on all critical quality metrics, i.e. calorific value, ash content, and shatter index. Regarding calorific value, finer mesh granularity (50 mesh) significantly enhances energy content. This improvement occurs because reduced particle size minimizes moisture absorption and maximizes particle density, thereby concentrating combustible material. Concurrently, higher corn cob charcoal ratios substantially increase calorific value due to its inherently superior energy potential compared to coconut shell residue. For ash content, finer meshes reduce inorganic residues as denser structures facilitate volatile release during combustion, while corn cob dominance further minimizes ash owing to its lower inherent ash fraction. Mechanically, finer mesh particles enhance structural integrity (lower shatter index) through improved inter-particle bonding and compact density under extrusion. Similarly, corn cob-rich blends demonstrate superior impact resistance. Critically, these interdependent trends demonstrate that optimizing both particle size reduction and corn cob enrichment simultaneously maximizes energy density [12], minimizes waste residues [23], and ensures mechanical robustness in extruded briquettes [24].

4 Conclusions

This study shows that the preform temperature setting plays a critical role in the success of the PET bottle stretch blow molding process. Heating the preform to 80°C produces significantly better results than 70°C, as this temperature exceeds the glass transition temperature (Tg) of PET, enabling sufficient elasticity for effective biaxial molecular orientation. This optimization is reflected in two primary quality indicators: more uniform wall thickness distribution and a significant reduction in product defects. Precise temperature control during the heating stage is therefore essential for regulating plastic deformation and improving the geometric and mechanical quality of PET bottles. In addition to temperature, blowing time also strongly influences product quality. A 0.50-second delay blow combined with a 0.50-second low blow enables controlled expansion and promotes balanced molecular orientation and crystallization. The delay period allows PET molecules to adjust to axial stretching by the stretch rod before high pressure is applied, resulting in more uniform material distribution. These findings have practical implications for semi-automatic machines used in laboratory-scale and small-to-medium production. The combination of an 80°C preform temperature and 0.50-second blowing time can serve as an operational reference to improve product consistency, reduce waste, and enhance production efficiency.

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