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Influence of Selected Processing Variables on Quality Attributes of Cocoa Pod-Husk Pellets

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Abstract: Biomass fuel pellets exhibit variations in quality due to differences in feedstock sources. Monitoring processing parameters is crucial for converting biomass into high-quality energetic pellets. This study examined the effects of selected parameters on the properties of cocoa pod husk pellets produced using a modified pelleting machine. The pellets were produced by varying the compression ratio (0.8, 1.0, 1.2), moisture content (10, 15, 20%) and binder quantity (0, 2.5, 5 wt%). A Box-Behnken design was employed to structure the experiment. The pellets were analyzed for density, proximate composition (moisture, volatile matter, fixed carbon, and ash contents), and higher heating value to assess their quality. The results were subjected to ANOVA at a 95% confidence level. The cocoa pod husk pellets had a bulk density of 0.28-0.41 g/cm³, moisture content of 13.22-19.30% (db), volatile matter of 48.61-57.83%, fixed carbon of 21.25-23.10%, ash content of 3.49-12.99%, and higher heating values of 18.28-19.30 MJ/kg. Significant differences were observed at the 95% confidence level ($p \leq 0.05$). Compression ratio, binder quantity and moisture content were found to affect the physicochemical properties of the pellets.

Keywords: biomass; cocoa pod husk; pellets; biofuel; compression ratio

1. Introduction

Nigeria spans over 98.3 million hectares, with more than 35% (34 million hectares) under cultivation, making agriculture the largest sector of the nation's economy [1]. Agricultural activities generate residues rich in carbohydrates and lignin, which can be harnessed for renewable energy production [2]. The use of bio-residues as a renewable energy source offers a sustainable solution to meet the growing energy needs of the global population [3]. In 2004, Jekayinfa and Scholz [4] estimated that the energy potential of agricultural residues in Nigeria was equivalent to 20.81 million tons of oil, covering approximately 82% of the country's annual energy consumption.

Nigeria is currently the fourth-largest producer and third-largest exporter of cocoa globally, having recently overtaken Ecuador [5]. The country accounts for 6.5% of global cocoa production, ranking behind Ivory Coast, Indonesia, and Ghana. Cocoa is predominantly grown in southwestern states, including Ondo, Oyo, Osun, Ogun, and Ekiti [6]. Cocoa pod husks (CPH), a byproduct of cocoa farming, are abundant, with around 1 million tonnes produced annually. While some of the husks are used as animal feed, much remains underutilized, leading to waste accumulation and the spread of black pod disease when left on plantations [7].

Effective management of agricultural residues is essential for preventing frequent fire outbreaks caused by bush burning, which can destroy cocoa and kola pod heaps and reduce plantation productivity. Additionally, there is a pressing need for alternative energy sources to meet Nigeria's growing energy demands. As the world's population increases, interest in using agricultural residues for renewable energy has grown.

The use of biomass for renewable energy is critical to combating climate change, as deforestation and fossil fuel consumption are major contributors. Biomass energy can help reduce global warming

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by replacing carbon-rich fossil fuels [8]. Accumulated cocoa pod husks can cause waterlogging and occupy valuable agricultural space, adversely affecting crop production. Densifying these residues can address these issues, improve environmental conditions, and enhance agricultural productivity.

Biomass and its derivatives hold substantial potential to replace fossil fuels and be integrated into existing energy technologies [9]. However, biomass's complex nature requires thorough investigation into manufacturing parameters to understand its self-bonding mechanisms during densification, which can improve its use as a fuel [10]. Previous research has explored the densification of various biomass types, including corncob [12,13], poplar wood [14], Mitrogyna ciliata [15], and livestock feed [16], focusing on how process and material parameters affect the final product. In Nigeria, pelletizing machines have traditionally been used to produce animal feed. However, a recent study by Jekayinfa et al. [17] adapted this technology for renewable energy production from biomass, specifically focusing on the effects of processing parameters (compression ratio, moisture content, and feedstock conditioning) on the physicochemical properties of cocoa pod husk (CPH) pellets.

2. Materials and Methods

2.1. Description of the Pelleting Machine

The modified pelletizing machine developed by Jekayinfa et al. [17] was used for this study. The machine consists of a compression chamber, an auger and a die plate. The compression chamber, or barrel, is where pressure is applied to the material being pelletized. It is made of cast iron, with a thickness of 10 mm, an internal diameter of 80 mm, and a length of 200 mm. The chamber has a hopper opening at the top, measuring 90 mm in diameter, which serves as the inlet for materials to be pelletized. The barrel is attached to the machine's frame via tentacle-like arms for support.

The auger, also made of cast iron, transports the material from the bottom of the hopper to the die plate. It has a 25 mm diameter shaft, an external diameter of 70 mm, a flight measuring 22.5 mm, and a pitch of 50 mm. The die plate acts as a back wall, retaining the pressure generated by the auger, while its perforations (die holes) allow the compressed material to exit the chamber as pellets. The die plate is made of mild steel, with a diameter of 100 mm and a thickness of 6 mm. It contains 48 cylindrical die holes, each 5 mm in diameter, through which the material is extruded. The orthographic projection and exploded view of the pelletizer are shown in Figure 1a and b [17].

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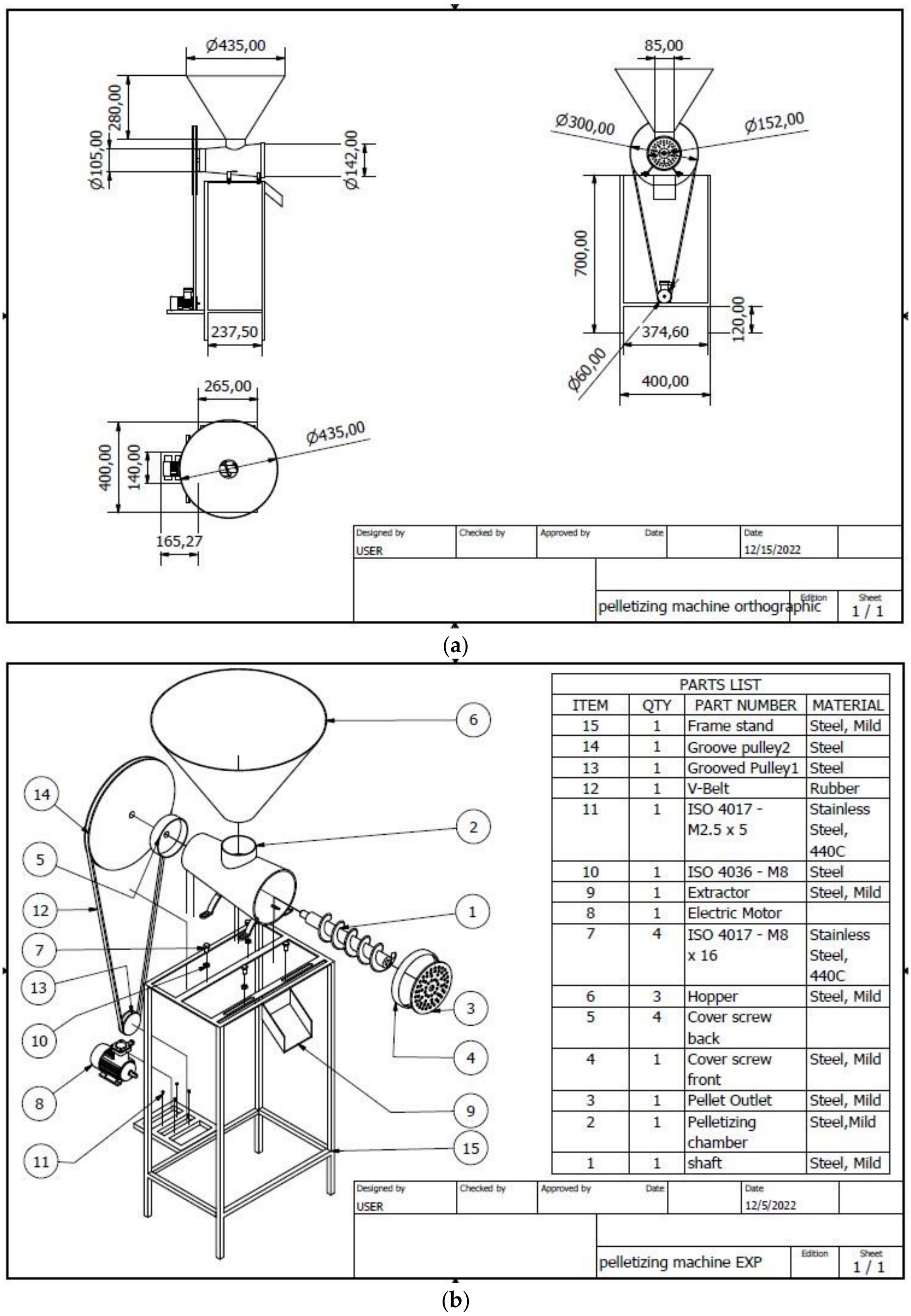

Figure 1. (a) Orthographic (third angle) view of the pelletizing machine. (b) Exploded views of the machine [7].

2.2. Experimental Procedure

Sample Sourcing and Preparation: Cocoa pod husk used for this study was sourced from the crop processing unit of the Cocoa Research Institute of Nigeria (CRIN), Ibadan. The pod husks were ground to powdery form using attrition mill, materials were bagged for further processing.

Preparation of binder: starch was used as a binding agent for this study. A 100 mL of distilled or deionized water was placed in a 250 mL beaker and brought to boiling point on a hot plate. A smooth paste was made with 1 g of soluble starch and a small volume (several millilitres) of distilled water. The boiling water was gently poured inside the bucket containing the paste and stirred gently until a firm viscous starch solution is obtained. The starch solution was allowed to cool to room temperature before usage.

Feedstock Conditioning: The moisture content of pellets was determined using ASTM E871 [18] standard method. According to the standard, moisture content of the samples was determined by oven-drying method. A known mass of sample (W_i) was dried in an oven at 105 ± 1°C until three consecutive weights (W_f) of sample is equal [19]. The percent moisture in the analysis sample is calculated using Equation 1 [20].

$$moisture\ in\ analysis\ sample = \frac{W_i - W_f}{W_i} \times 100\%, \quad (1)$$

where: W_i is the initial weight (g), and W_f is the final weight (g)

The feedstock materials were brought to the required moisture content of 10, 15 and 20% (wb) by adding an adequate weight of water required using Equation 2 [21] for moisture content determination.

$$weight\ of\ water = \%\ MC\ \times weight\ of\ dry\ matter, \quad (2)$$

The binder was added to the ground feedstock in three different proportions: 0%, 2.5%, and 5% starch content by weight, following the EN 14961 [22] standard in preparation for the experiment. The feedstock was measured, and the appropriate binder percentage was calculated. The materials were then thoroughly mixed in a bowl using a pestle until a uniform paste was achieved.

Experimental Setup: The experiment was conducted using the modified pelleting machine, which was connected to a power source. A known mass and volume of feedstock were poured into the hopper, and the machine was operated until all the material was processed into pellets. The collected pellets were weighed, dried, and stored. The factors considered for the experiment included the die compression ratio (0.8, 1.0, 1.2), moisture content (10%, 15%, 20%), and binder content (0%, 2.5%, 5%).

Design of Experiment: A Box-Behnken design was used to structure the experiment, utilizing Design Expert 12.0.3.0 software. Three independent variables at three levels each—compression ratio (0.8, 1.0, 1.2), binder content (0%, 2.5%, 5%), and moisture content (10%, 15%, 20%)—were studied. The dependent variables analyzed were bulk density, moisture content, volatile matter, fixed carbon, ash content, and Higher Heating Value (HHV). A total of 15 experiments were generated. The pellet characteristics were subjected to analysis of variance (ANOVA), with results accepted based on a significance level of $P \leq 0.05$.

Determination of Pellet Characteristics: Bulk Density: The bulk density was determined following ASTM E873 [23] test procedures. A sample of known weight was packed into a measuring cylinder, and the bulk density was calculated by dividing the sample weight (g) by the measured volume (cm^3). The measurement was repeated in triplicate, and the average value was recorded. Bulk density was calculated using the formula in Equation 3 [24].

$$B_D = \frac{W_1 - W_0}{V}, \quad (3)$$

Where: B_D is the bulk density (g/cm^3), W_1 is the mass of the container with sample (g), W_0 is the mass of the container (g), and V is the volume occupied by pellet (cm^3).

Moisture Content: The moisture content of the pellets was determined using the method previously described.

Ash Content: The ash content of the pellets was measured following ASTM D1102 [25] standard procedures. A clean, empty crucible was ignited in a muffle furnace at 525 ± 25°C for 30 minutes, then cooled slightly in a desiccator. The crucible was weighed on an analytical balance to the nearest 0.1 mg, and a known mass of the test specimen was placed inside. The crucible was then placed in the furnace at about 100°C, with the temperature gradually increasing to 525°C to carbonize the sample without flaming [26].

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When specimen is completely combusted as indicated by the absence of black particles, the crucible was removed from the furnace and allowed to cool in a desiccator. The weight of the crucible with ash was taken and recorded. The ash content is calculated using Equation 4 [27].

$$Ash\ (\%) = \frac{(W_{CA} - W_C) \times 100}{B}, \quad (4)$$

Where: W_C is the weight of empty crucible (g), W_{CA} is the weight of crucible with ash (g), B is the weight of test sample (g).

Volatile Matter Content: ASTM E872 [28] was used to determine the volatile matter of the produced pellets. Volatile matter is determined by establishing the loss in weight resulting from heating text sample under controlled conditions. A crucible with cover was weighed and record as W_c. A known mass of sample was placed in the crucible, covered and weighed and record as initial weight, W_i. The covered crucible with sample was placed in the furnace and was maintained at a temperature of 950 ± 20°C for a total of exactly 7 min. The crucible was removed from the furnace and allowed to cool in a desiccator. The cooled, covered crucible with sample was weighed and record as final weight, W_f. the weight loss is calculated in percentage as shown in Equation 5 [29]

$$A = 100 \times \frac{(W_i - W_f)}{(W_i - W_c)}, \quad (5)$$

Where: A is the weight loss (%), W_c is the weight of crucible and cover (g), W_i is the initial weight (g), W_f is the final weight (g).

The volatile matter (%) in the analysis sample is calculated using Equation 6

$$VM = A - B, \quad (6)$$

Where: VM is the volatile matter (%), A is the weight loss (%), B is the moisture, (%)

Fixed Carbon Content: this was determined based on methods of ASTM E870 [30] standard, fixed carbon was calculated as difference of the summation of moisture, ash and volatile matter content from 100 using Equation 7 [31].

$$FC = 100\% - (MC + AC + VM), \quad (7)$$

Where: FC is the fixed carbon (%), MC is the moisture content (%), AC is the ash content (%), VM is the volatile matter (%).

Higher Heating Value (HHV): The higher heating value (HHV) of the pellets were determined using Equation 8 [32] as a function of fixed carbon content thus:

$$HHV = 0.196FC + 14.119, \quad (8)$$

Where: HHV= higher heating value (MJ/kg), FC = fixed carbon content of biomass fuel (wt%)

3. Results

The quality attributes of the CPH at varying processing condition is presented in Table 2.

Table 2. Quality Characteristics of Cocoa Pod Husk Pellet.

Run	A	B (%/w)	C (%)	BD (g/cm³)	PMC (%)	PVM (%)	PFC (%)	ASH (%)	HHV (MJ/kg)
1	1.2	0.0	15	0.360	18.02	50.82	22.31	8.44	18.492
2	1.0	5.0	20	0.290	16.45	55.75	21.50	5.88	18.894
3	1.0	0.0	10	0.337	15.50	51.74	21.85	10.45	18.402
4	0.8	5.0	15	0.291	15.77	55.45	21.30	6.86	18.831
5	1.0	0.0	20	0.360	16.28	48.61	22.82	11.85	18.592
6	1.2	2.5	10	0.409	16.67	54.14	21.25	7.44	18.284
7	0.8	0.0	15	0.354	13.22	51.26	23.10	12.99	18.647
8	1.0	2.5	15	0.354	16.00	53.97	22.03	8.00	18.437
9	1.0	2.5	15	0.323	16.13	54.52	21.94	7.41	18.419
10	0.8	2.5	20	0.340	15.67	52.76	22.03	9.04	18.437

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11	1.0	5.0	10	0.332	16.19	57.83	21.35	4.91	18.304
12	1.0	2.5	15	0.340	15.60	53.41	22.00	8.94	18.431
13	1.2	2.5	20	0.333	19.30	50.40	23.00	7.30	18.627
14	0.8	2.5	10	0.280	13.83	56.08	21.93	8.63	18.418
15	1.2	5.0	15	0.370	19.12	55.63	22.33	3.49	18.496

A: compression ratio; B: Percentage binder; C: moisture content; BD: pellet bulk density; PMC: pellet moisture content; PVM: pellet volatile matter; PFC: pellet fixed carbon; ASH: pellet ash content; HHV: pellet higher heating value.

3.1. Bulk Density

The effect of compression ratio, binder, and CPH moisture content on bulk density is illustrated in Figure 2. Figure 2a presents the influence of die compression ratio on the bulk density of the pellets. The highest bulk density value of 0.368 g/cm³ was observed at a compression ratio of 1.2, while the lowest value of 0.316 g/cm³ occurred at a compression ratio of 0.8. These results fall within the range of 0.24–0.96 g/cm³ reported by Okewole and Igbeka [33] for fish feed pellets produced using a pelleting press. Jekayinfa et al. [34] also found a bulk density range of 0.282–0.793 g/cm³ for rice bran pellets. The data indicate that bulk density increases as the die compression ratio rises, from 0.32 g/cm³ at a ratio of 0.8 to 0.36 g/cm³ at 1.2.

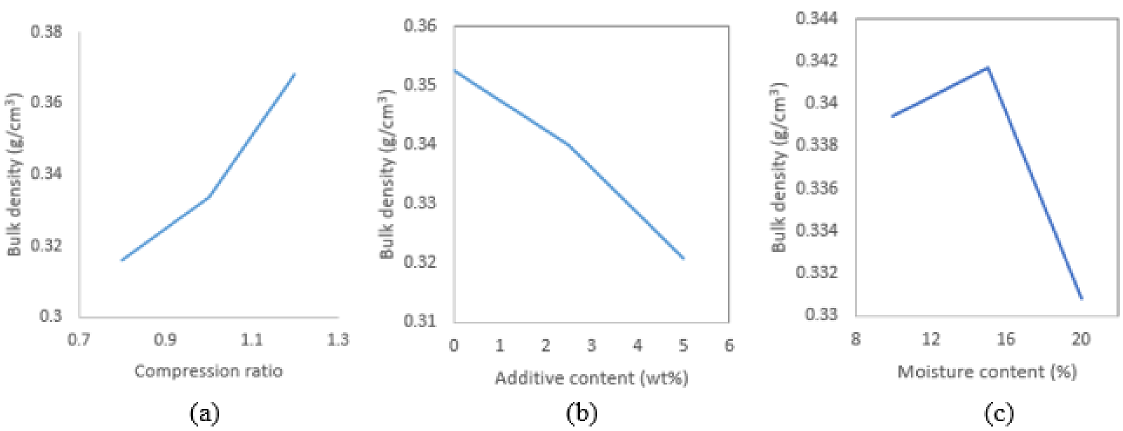

Figure 2. Bulk density of Cocoa Pod-Husk (CPH) Pellets as affected by: (a) Compression ratio, (b) Additive Content, (c) Moisture content.

Figure 2b shows the impact of binder content on pellet bulk density, with the highest value of 0.353 g/cm³ occurring at 0.0 wt% binder and the lowest value of 0.321 g/cm³ at 5.0 wt% binder. This is lower than the 0.609 g/cm³ reported by Tasarov et al. [35] for wood pellets. The figure also reveals that bulk density decreases with increasing binder content. The use of binding agents affects pellet length, and larger particle sizes, higher moisture content, and increased production temperature and pressure tend to raise bulk density [36].

The bulk density (BD) of the CPH pellets increases as the binder content decreases and the compression ratio increases. However, it decreases with higher CPH moisture content. An opposite effect, where bulk density increased with moisture content, was reported by Okewole and Igbeka [33]. The regression equation representing the relationship between the factors and their interaction is shown in Equation 9. The model's significance was evaluated using analysis of variance (ANOVA) at a 95% confidence level. The ANOVA results, as shown in Table 3, indicate that the interaction between compression ratio and binder content, compression ratio and moisture content, and binder content and CPH moisture content all have a significant effect on the bulk density of CPH pellets. According to the regression equation, an increase in compression ratio and the interaction between compression ratio and binder content will lead to a higher bulk density of the CPH pellets. Conversely, an increase in binder content, moisture content, the interaction between compression

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ratio and CPH moisture content, and the interaction between binder content and CPH moisture content will reduce the bulk density of the CPH pellets.

$$BD = 0.3382 + 0.0259A - 0.0159B - 0.0043C + 0.0182AB - 0.0340AC - 0.0163BC \quad (9)$$

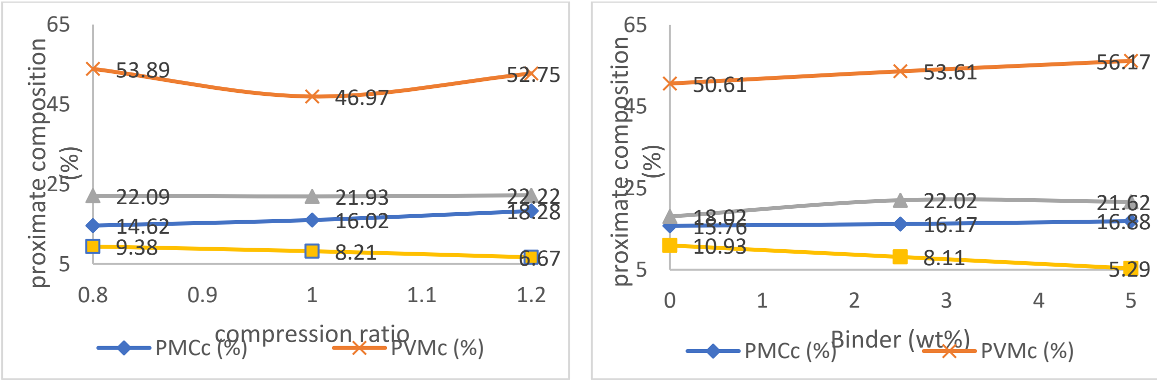
Table 3. Analysis of variance results for cocoa pod husk pellets bulk density.

Source	Sum of Squares	df	Mean Square	F-value	p-value	Conclusion
Model	0.0145	6	0.0024	17.04	0.0004	significant
A-CR	0.0053	1	0.0053	37.65	0.0003	significant
B-additive	0.0020	1	0.0020	14.32	0.0054	significant
C-MC	0.0001	1	0.0001	1.04	0.3384	not significant
AB	0.0013	1	0.0013	9.30	0.0158	significant
AC	0.0046	1	0.0046	32.53	0.0005	significant
BC	0.0011	1	0.0011	7.44	0.0260	significant
ABC	0.0000	0				
Pure Error	0.0005	2	0.0002			
Cor Total	0.0157	14				
Fit Statistics			**Std. Dev.**	0.0119	**R^2**	0.9274
			Mean	0.3382	**Adj. R^2**	0.8730
			C.V.%	3.52	**Pred. R^2**	0.7426
					Adeq Prec.	15.2426

3.2. Proximate Composition

3.2.1. Proximate Composition as Affected by Compression Ratio

It was observed that the moisture content of CPH pellets increases with higher compression ratios. The highest moisture content of 18.28% (db) was observed at a compression ratio of 1.2, while the lowest was 14.62% at a compression ratio of 0.8. Additionally, the volatile matter in the CPH pellets initially decreased with increasing compression ratio but then increased. The highest volatile matter, 53.89%, was found at a compression ratio of 0.8, and the lowest, 46.97%, was at a compression ratio of 1.0. Fixed carbon content decreased initially with higher compression ratios before increasing again. The highest fixed carbon content, 22.22%, was at a compression ratio of 1.2, and the lowest, 21.93%, was at a compression ratio of 1.0. The ash content also decreased with higher compression ratios, with the highest value of 9.38% at a compression ratio of 0.8 and the lowest of 6.67% at a ratio of 1.2. Figures 3a to 3c illustrate the effects of compression ratio, binder, and moisture content on the proximate composition of CPH pellets. These values differ significantly from those reported by Sanchez et al. [37] for densified fuel made from waste wood in Piura, Peru, which had 10% moisture, 83.41% volatile matter, 15.29% fixed carbon, and 1.3% ash content. Similarly, Ikelle and Chukwuma [38] reported 2.87% moisture, 30.42% volatile matter, 45.01% fixed carbon, and 21.70% ash content for briquettes made from 80% coal and 20% corncob, noting that the higher fixed carbon value was due to the addition of coal.



(a) (b)

Figure 3. Effect of Processing Parameters on Cocoa Pod Husk Pellets Proximate Composition; (a) Compression Ratio, (b) Binder.

3.2.2. Proximate Composition as Affected by Binder Content

Figure 3b shows the effect of binder on CPH pellet proximate compositions. The moisture content and volatile matter increased with an increase in binder. The highest and lowest value of moisture content of 16.88 and 15.76% was obtained at 5.0 and 0.0 wt% binder, respectively and the corresponding values recorded for volatile matter content are 56.17 and 50.61% obtained at 5.0 and 0.0 wt% binder, respectively. For fixed carbon content, it was observed in Figure 3b, that fixed carbon increases with an increase in binder content and later decreased. The highest and lowest value of 22.02 and 18.02% was obtained at 2.5 and 0.0 wt% binder, respectively for fixed carbon content. Also, CPH pellet's ash content showed a decrease with increasing binder. The highest value of 10.93% for ash content was obtained at 0.0 wt% binder and the lowest value of 5.29% was obtained at 5.0 wt% binder. The result obtained is within the 12 – 18% obtained by Čolović *et al.* [39] for switchgrass pellets.

3.2.3. Proximate Composition as Affected by Moisture Content

Figure 4 shows the effect of CPH moisture content on CPH pellet's proximate composition. It was observed that moisture content, fixed carbon and ash contents increase with increasing CPH moisture content and volatile matter show a decrease with increasing CPH moisture content. The highest value of 19.93% moisture content, 22.34% fixed carbon and 8.52% ash contents were obtained at 20% CPH moisture content and the lowest value of 15.55% moisture content, 21.6% fixed carbon and 7.86% ash contents were obtained at 10% CPH moisture content. For volatile matter content, the highest and lowest value of 54.95 and 51.88% were obtained at 10 and 20% CPH moisture content, respectively. The values obtained are similar to the mean values 80.22% volatile matter, 15.83% fixed carbon and 4.43% ash contents reported by Liu *et al.* [27] for wood and rice husk pellets. The high value of volatile matter includes the moisture content present in the material which was not determined separately. Jindaporn *et al.* [40] studied mixing ratios and binder types on properties of biomass pellets and recorded 8.53,67.21, 3.22 and 21.03% for moisture, volatile matter, ash and fixed carbon contents, respectively. Gonzalez *et al.* [41] recorded similar increase in volatile matter with decreasing moisture content and binder addition. The values obtained are higher in volatile matter content and fixed carbon than the values obtained in this study. This may be due to the type of materials used for pellet production.

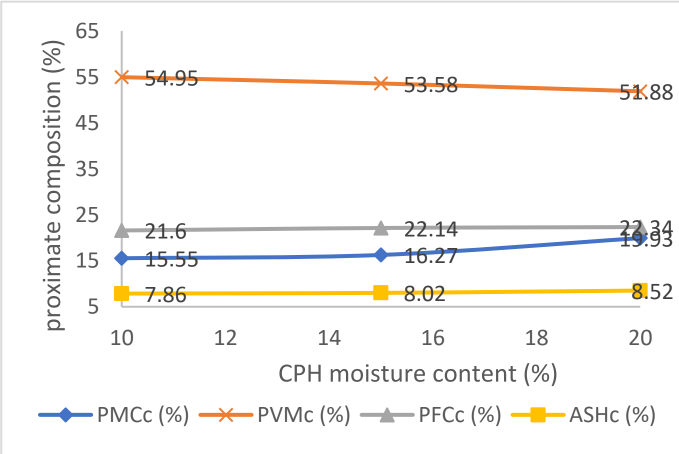


Figure 4. Effect of Moisture Content on Cocoa Pod Husk Pellets Proximate Composition.

The regression equations predicting the Moisture Content (MC) of pellets, Volatile Matter (VM), Fixed Carbon Content (FCC), Ash Content and Higher Heating Value (HHV) is presented in Equations 10 – 14 respectively.

$$MC = 16.25 + 1.83A + 0.5637B + 0.6887C - 0.3625AB + 0.1975AC - 0.1300BC, \quad (10)$$

$$VM = 53.49 - 0.57A + 2.78B - 1.53C + 0.1550AB - 0.1050AC + 0.2625BC, \quad (11)$$

$$FC = 21.99 + 0.0662A - 0.45B + 0.3712C + 0.455AB + 0.4125AC - 0.205BC + 0.2212A^2 + 0.0488B^2 - 0.1588C^2, \quad (12)$$

$$ASH = 8.11 - 1.36A - 2.82B + 0.3300C + 0.2950AB - 0.1375AC - 0.1075BC, \quad (13)$$

The results of ANOVA test of significance of Moisture Content (MC), Volatile Matter (VM), Fixed Carbon Content (FCC), and Ash Content is presented in Tables 4, 5, 6, and 7, respectively.

Table 4. ANOVA results for cocoa pod husk pellets moisture content.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	33.80	6	5.63	12.01	0.0013	Significant
A-CR	26.72	1	26.72	56.93	< 0.0001	Significant
B-additive	2.54	1	2.54	5.42	0.0483	Significant
C-MC	3.80	1	3.80	8.09	0.0217	Significant
AB	0.5256	1	0.5256	1.12	0.3208	not significant
AC	0.1560	1	0.1560	0.3325	0.5801	not significant
BC	0.0676	1	0.0676	0.1440	0.7142	not significant
ABC	0.0000	0				
Pure Error	0.1526	2	0.0763			
Cor Total	37.56	14				
Moisture cocoa			**Std. Dev.**	0.6851	**R²**	0.9000
			Mean	16.25	**Adjusted R²**	0.8251
			C.V.%	4.22	**Predicted R²**	0.5232
					Adeq Precision	11.6832

Table 5. Analysis of variance result for cocoa pod husk pellets volatile matter.

Source	Sum of Squares	df	Mean Square	F-value	p-value	Conclusion
Model	83.61	6	13.93	17.85	0.0003	Significant
A-CR	2.60	1	2.60	3.33	0.1055	not significant

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B-additive	61.77	1	61.77	79.11	< 0.0001	significant
C-MC	18.82	1	18.82	24.10	0.0012	significant
AB	0.0961	1	0.0961	0.1231	0.7348	not significant
AC	0.0441	1	0.0441	0.0565	0.8181	not significant
BC	0.2756	1	0.2756	0.3530	0.5688	not significant
ABC	0.0000	0				
Pure Error	0.6161	2	0.3080			
Cor Total	89.85	14				
VM cocoa			**Std. Dev.**	0.8836	**R^2**	0.9305
			Mean	53.49	**Adjusted R^2**	0.8783
			C.V.%	1.65	**Predicted R^2**	0.6899
					Adeq Precision	14.2882

Table 6. Analysis of variance results for fixed carbon content of cocoa pod husk pellets.

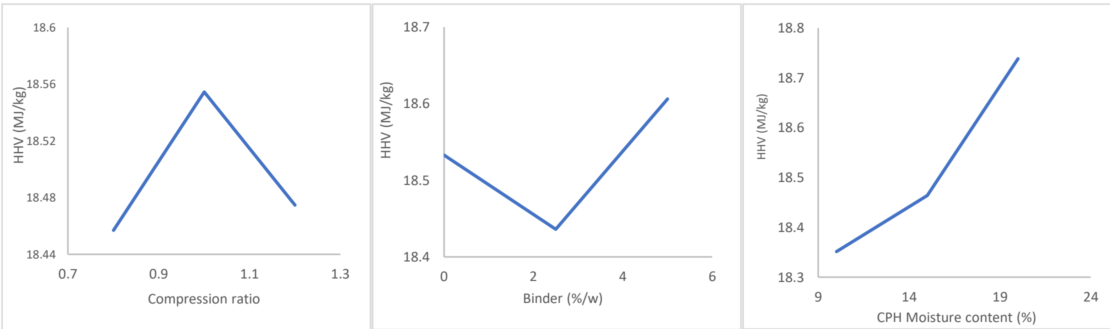
Source	Sum of Squares	df	Mean Square	F-value	p-value	Conclusion
Model	4.74	9	0.5264	36.90	0.0005	significant
A-CR	0.0351	1	0.0351	2.46	0.1775	not significant
B-additive	1.62	1	1.62	113.56	0.0001	significant
C-MC	1.10	1	1.10	77.29	0.0003	significant
AB	0.8281	1	0.8281	58.05	0.0006	significant
AC	0.6806	1	0.6806	47.71	0.0010	significant
BC	0.1681	1	0.1681	11.78	0.0186	significant
A^2	0.1807	1	0.1807	12.67	0.0162	significant
B^2	0.0088	1	0.0088	0.6151	0.4684	not significant
C^2	0.0931	1	0.0931	6.52	0.0510	not significant
ABC	0.0000	0				
Pure Error	0.0042	2	0.0021			
Cor Total	4.81	14				
FC cocoa			**Std. Dev.**	0.1194	**R^2**	0.9852
			Mean	22.05	**Adjusted R^2**	0.9585
			C.V.%	0.5417	**Predicted R^2**	0.7747
					Adeq Precision	18.8168

Table 7. Analysis of variance (ANOVA) result for cocoa pod husk pellets ash content.

Source	Sum of Squares	df	Mean Square	F-value	p-value	Conclusion
Model	79.84	6	13.31	20.90	0.0002	significant
A-CR	14.72	1	14.72	23.12	0.0013	significant
B-binder	63.79	1	63.79	100.21	< 0.0001	significant
C-MC	0.8712	1	0.8712	1.37	0.2757	not significant
AB	0.3481	1	0.3481	0.5468	0.4807	not significant
AC	0.0756	1	0.0756	0.1188	0.7392	not significant
BC	0.0462	1	0.0462	0.0726	0.7944	not significant
ABC	0.0000	0				
Pure Error	1.19	2	0.5954			
Cor Total	84.94	14				
			Std. Dev.	0.7979	**R^2**	0.9400
			Mean	8.11	**Adj. R^2**	0.8951
			C.V.%	9.84	**Pred. R^2**	0.7393
					Adeq Prec.	15.3383

3.2. Higher Heating Value

Figure 5a- c show the effect of compression ratio, binder and CPH moisture content, respectively on HHV of the CPH pellets. Figure 5a shows that HHV increases with increasing compression ratio to a maximum of 18.55 M/kg and further increase in compression ratio decreases HHV of CPH pellets. Figure 5b shows a decrease in HHV with increasing binder to a minimum of 18.43 MJ/kg and further increases in binder content increases HHV. Finally, Figure 5c shows that HHV increases with increasing CPH moisture content. In each case, the highest and lowest value 18.55 and 18.46 MJ/kg were obtained at 1.0 and 0.8 compression ratio, respectively. The highest value of 18.61 MJ/kg was obtained at 5.0 wt% binder and lowest value of 18.44 MJ/kg for HHV was obtained at 2.5 wt% binder. Likewise, the highest value and lowest value of 18.74 and 18.35 MJ/kg were obtained at 20 and10% CPH moisture content, respectively. The result obtained is higher than the 14.98 MJ/kg obtained by Iftikhar *et al*. [42] for wheat and rice straw pellets. Ferreira *et al*. [43] studied the use of waste wood pellets as an alternate energy source and recorded 20.39 MJ/kg higher heating value for pellets of 50 – 50% *Dinizia excelsa* and *Manilkara elata.* Their values are however higher than the values obtained in this study, this may be due to the pellet's material being a mixture of two woody biomass.



(a) **(b)** **(c)**

Figure 5. Effects of (a) compression ratio, (b) binder and (c) moisture content on higher heating value of CPH pellets.

Equation 14 shows the regression equation for HHV of cocoa pod husk pellets. The equation shows that increases in compression ratio, CPH moisture content will increase HHV of cocoa pod husk pellets while increases in binder will decrease HHV of cocoa pod husk pellets. The result of the ANOVA presented in Table 8 shows that the model P-value and F-value of 0.0046 and 46.74, respectively signifies that the models in Equation 4.6 is significant and the R^2 value of 0.9929 implies that the equation can predict HHV of CPH pellets with 99.29% accuracy.

$$HHV_c = 18.43 + 0.0082A - 0.0715B + 0.0846C + 0.0795AB + 0.0809AC - 0.0165BC + 0.0363A^2 + 0.0262B^2 - 0.0241C^2, \quad (14)$$

Table 8. ANOVA result for HHV of CPH pellets.

Source	Sum of Squares	df	Mean Square	F-value	p-value	Conclusion
Model	0.1455	9	0.0162	46.74	0.0046	significant
A-CR	0.0003	1	0.0003	0.9254	0.4070	not significant
B-binder	0.0136	1	0.0136	39.45	0.0081	significant
C-MC	0.0344	1	0.0344	99.32	0.0021	significant
AB	0.0108	1	0.0108	31.35	0.0113	significant
AC	0.0261	1	0.0261	75.58	0.0032	significant
BC	0.0005	1	0.0005	1.35	0.3295	not significant
A^2	0.0037	1	0.0037	10.78	0.0463	significant
B^2	0.0013	1	0.0013	3.81	0.1459	not significant
C^2	0.0016	1	0.0016	4.74	0.1177	not significant

ABC	0.0000	0				
Pure Error	0.0002	2	0.0001			
Cor Total	0.1466	12				
			Std. Dev.	0.0186	**R^2**	0.9929
			Mean	18.46	**Adjusted R^2**	0.9717
			C.V.%	0.1008	**Predicted R^2**	NA[(1)]
					Adeq Precision	21.4865

5. Conclusions

The study examined how processing parameters affect the quality attributes of cocoa pod-husk pellets. The parameters investigated included moisture content, binder ratio, and compression ratio, while the quality attributes measured were bulk density, moisture level, ash content, volatile matter, and higher heating value. The findings revealed that the compression ratio, binder ratio, and feedstock moisture content significantly influence the bulk density, ash content, and fixed carbon content of the pellets, which in turn affect their calorific value. Specifically, the higher heating value of the pellets increased with higher compression ratios, binder content, and feedstock moisture levels. The results indicate that cocoa pod husk pellets are viable for power generation and can serve as an alternative to raw biomass. Additionally, mathematical models were developed to estimate the physicochemical properties of cocoa pod-husk pellets.

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