

Evaluation of the Physical and Energetic Properties of Briquettes Based on Agricultural Residues for Use in Food Smoking

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Abstract

In West Africa, promoting renewable energy and recovering energy from agricultural waste are sustainable alternatives in the face of pressure on natural resources. Thus, this study evaluated the energy performance of briquettes made from agricultural residues that can be substituted for wood for fish smoking. Five types of briquettes were developed from rice husks (BriqRi), pineapple peels (BriqAn), and three combinations: rice husk-pineapple peels (BriqRiAn), pineapple peels-orange (BriqAnO), and rice husk-pineapple peels-orange (BriqRiAnO). The binder used was cassava starch. The physical and energetic characteristics of the raw materials and those of the formulated briquettes were evaluated before and after sun-drying. Our study shows that rice hulls and dried orange peels have the best energy performance, with low moisture (9.33% and 10.99% respectively) and a high flash point (208.4°C and 224°C respectively). Regarding dried briquettes, BriqRi had the highest calorific value (2872.25 Kcal/kg), low moisture (9.35%), high ash content (14.32%), and the highest mechanical strength (10). BriqAnO had the lowest

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impact index (7.00), the highest moisture content (12.03%) and the highest flash point (213.60°C). At the end of our study, we can conclude that BriqRi briquettes are one of the best candidates for replacing firewood in fish smoking due to their physical and energetic characteristics and high ash content, which allows smoking to continue without PAH emissions after the disappearance of organic matter.

Keywords

Smoked Fish, Smoking Briquette Formulation, Agricultural Residues, Moisture

1. Introduction

In West and Central Africa, nearly 79% of deforested land is converted to agricultural land, 13% to pasture, while the rest is used for domestic energy [1]-[4]. This dynamic leads to accelerated degradation of forest ecosystems, with environmental and health impacts (loss of biodiversity, destruction of carbon sinks) by contributing to climate change, emissions of harmful gases (CO₂, CH₄, NO_x, SO₂) and fine particles responsible for respiratory and cardiovascular diseases [5]-[7]. In response to this situation, the promotion of renewable energies and waste-to-energy conversion appears to be sustainable alternatives capable of reducing pressure on natural resources, improving living conditions, and contributing to energy security [4] [6] [8]-[12].

In Benin, traditional smoking of fish and meat, which relies heavily on firewood, remains an essential preservation method, reducing post-capture losses estimated at 20% [13]-[15]. In mangrove areas, individual energy consumption of wood and charcoal remains below estimated needs, revealing an energy deficit of nearly 36% [16] [17]. This increasing pressure on wood resources has led to the use of alternative fuels, some of which (e.g., plastic bags, cardboard packaging) pose significant health risks [18]-[20]. To address this challenge, agricultural residues (fruit peelings, rice husks) have been recycled into briquettes for smoking as a sustainable alternative [7] [15] [21]-[23]. Previous studies [24] experimented with the use of crop residues and fruit peelings as fuels for fish smoking in Benin. The same authors subsequently converted these residues into briquettes for fish smoking in Benin [15], proposing them as a sustainable alternative to firewood and other fuels. However, characterization of both the raw materials and the resulting briquettes in terms of physicochemical properties remains necessary to standardize production technology and identify the most suitable briquettes for smoking. This study, conducted in Southern Benin, therefore aims to evaluate the physicochemical and energy properties of local raw materials used in briquette production, as well as those of the briquettes themselves. This approach adds value by generating novel scientific data to guide the selection of the most suitable briquettes.

2. Materials and Methods

2.1. Materials

2.1.1. Experimental Framework and Sample Collection

The study was conducted at the Animal Biotechnology and Meat Technology Laboratory (LBATV) of the Abomey-Calavi Polytechnic School, University of Abomey-Calavi (EPAC) of the University of Abomey-Calavi in southern Benin, in collaboration with the Lafarge cement plant laboratory in Onigbolo and the Human Nutrition and Bio-Ingredient Valorization Laboratory of the Faculty of Agricultural Sciences of the University of Abomey-Calavi. The raw materials used are identical to those used by [15] and come from the same sources. These are rice husks, pineapple peels, orange peels, and cassava starch. The pineapple and orange peels were collected from local fruit retailers, and the rice husks were collected from a mini rice mill in southern Benin. The cassava starch was purchased at the local market from food vendors in Benin.

2.1.2. Pretreatment of Raw Materials

The pineapple and orange peels were sorted and dried for three and two weeks, respectively, in the sun after collection. The cassava starch was also dried for two weeks in the sun. The drying process took place during the dry season under average ambient conditions with a temperature of 30°C and relative humidity of 72%. Only the rice husks did not require a drying phase before use.

All these raw materials, with the exception of starch, were cleaned of impurities (stones, pieces of wood, plastic debris, etc.) after drying and then finely ground into small particles of 0.2 mm using an RX 9FQ-400 grinder (Henan, China).

Before drying, 10 g samples of each raw material except rice husks were taken and their moisture content was determined. After drying and just before grinding, samples of each raw material, including rice husks, were taken again and used for various analyses. Fifty (50) raw material samples were analyzed, with ten (10) samples per raw material for the various analyses. The analyses performed on the raw materials were moisture content, ash content, flash point temperature and time, and gross and dry lower calorific value. A mechanical piston hydraulic press consisting of six molds with a manual cylinder actuator (compression and extraction), with molds 6 cm high and 10 cm in diameter, was used to mold the briquettes.

2.2. Methods

2.2.1. Briquette Production

Agricultural residues (rice husks, orange peel, pineapple peel) and cassava starch, which had been dried and ground beforehand, were used to produce five (05) types of briquettes in accordance with the method used by [15], but using a mechanical piston hydraulic press to compact the briquettes for 6 minutes at a pressure of 150 MPa instead of the manual production described by these authors. The five formulas used to manufacture the five types of briquettes are:

- Rice husk briquettes (BriqRi): ground rice husks (53%) + Cassava starch (19%) + Water (28%)

- Pineapple peel briquettes (BriqAn): ground pineapple peel (53%) + Cassava starch (19%) + Water (28%)
- Rice husk and pineapple peel briquettes (BriqRiAn): ground rice husks (18%) + ground pineapple peel (19%) + cassava starch (25%) + water (38%)
- Pineapple peel and orange peel briquettes (BriqAnO): ground pineapple peel (19%) + ground orange peel (18%) + cassava starch (25%) + water (38%)
- Rice husk, pineapple peel, and orange peel briquettes (BriqRiAnO): ground rice husks (18%) + ground pineapple peel (18%) + ground orange peel (18%) + cassava starch (19%) + water (27%).

Five (5) batches of briquettes were produced for each type of briquette, and two briquettes were taken from each batch for various analyses, ten briquettes per formula and 50 briquettes in total were analyzed. The briquettes were dried in the sun for approximately 11 days to reach a moisture content of no more than 14%. They were then stored in a dry place until use.

2.2.2. Physicochemical, Thermal, and Mechanical Characteristics of Raw Materials and Briquettes

The samples taken from the raw materials and the briquettes were subjected to various analyses. These were carried out in accordance with the methodologies described by [6]. The raw material and briquette samples were ground before being used for analysis.

1) Moisture content of raw materials and briquettes

This was determined on samples of raw materials and briquettes taken and by drying each sample at 105°C in a ventilated oven until a constant weight was obtained, according to the method described by [6].

2) Ash content of raw materials and briquettes

The ash content of the raw material and briquette samples taken was assessed in accordance with the method described by [6]. Each sample was weighed in crucibles and heated to 550°C for 24 hours in a muffle furnace.

3) Temperature and time to reach flash point of raw materials and briquettes

According to the international standard [25], flash point is a measure of the tendency of a test sample to form a flammable mixture with air under controlled laboratory conditions. It is only one of many properties to consider when assessing the overall flammability risk of a material. Flash point is used in transportation and safety regulations to define flammable and combustible materials. It can indicate the possible presence of highly volatile and flammable substances in a relatively non-volatile or non-flammable material. This test method is used to measure and describe the properties of materials, products, or assemblies in response to heat and a test flame under controlled laboratory conditions. It is not intended to describe or assess the fire risk of materials, products, or assemblies under actual fire conditions. However, the results of this test method may be used as part of a fire hazard assessment taking into account all factors relevant to a given end use.

The flash point determination was carried out in accordance with [25]. Each sample was gradually heated at a constant rate with continuous stirring from

50°C, with a rise in 10°C increments, until ignition was observed and the ignition time was recorded.

4) Gross lower calorific value and dry lower calorific value

The lower calorific value (gross and dry) was determined for the raw materials and briquettes in a calorimeter according to method [26].

5) Drop Test

The Drop Test was performed only for briquettes in accordance with the method described by [27] and identified the five types of briquettes that have good impact resistance. The assessment grid for the impact resistance test results is presented in **Table 1**.

Table 1. Impact resistance test assessment grid.

Evaluation Criteria	Score	Resistance Rating
Briquette remained intact after free fall: no cracks or breaks	10	Very good
Briquette remained intact after free fall, but with cracks and slight edge breakage	[8 - 10[Good
Briquette broken into two or three pieces after free fall	[5 - 8[Weak
Briquette crumbled after free fall	[1 - 5[Very weak

2.2.3. Statistical Analyses

The Statistical Analysis System (SAS, 2012) software was used for data analysis. The Proc means procedure was used to calculate the means of the different variables. The General Linear Model (GLM) procedure was used for the analysis of variance, and the sources of variation taken were the type of raw material or the type of briquette. The F test was used to determine the significance of each effect of the analysis of variance model, and the calculated means were compared using Student's t-test.

3. Results

3.1. Physicochemical Properties of Rice Husks, Pineapple Peelings, and Orange Peelings, and Cassava Starch

The physicochemical characteristics of the raw materials used in the study are presented in **Table 2**. All parameters analyzed varied significantly from one raw material to another ($p < 0.001$).

Table 2. Physicochemical parameters of rice husks, pineapple peels, orange peels, and cassava starch (mean \pm standard deviation).

Parameters	Moisture before drying (%)	Moisture after drying (%)	Ash content (%)	Flash point temperature (°C)	Flash point time (Min)	Gross lower calorific Value (Kcal/kg)	Dry lower calorific Value (Kcal/kg)
Rice husks	ND	9.33 \pm 0.46c	18.85 \pm 0.11a	208.4 \pm 7.53ab	6.4 \pm 0.89c	2672.61 \pm 107.54b	2900.73 \pm 99.80b

Continued

Pineapple peelings	81.08	12.47	9.45	196.4	12.4	2919.08	3532.08
	±	±	±	±	±	±	±
	0.74a	0.40b	0.42b	14.44b	4.33b	38.16a	39.93a
Orange peelings	51.10	10.99	9.19	224	7.2	2971.4	3500.94
	±	±	±	±	±	±	±
	4.09b	1.08bc	0.42b	21.54a	1.64c	86.94a	120.13a
Cassava starch	46.56	15.21	0.48	168	24.4		
	±	±	±	±	±	ND	ND
	4.45c	0.37a	0.02c	8.03c	1.67a		
Significance test	***	***	***	***	***	***	***

*** $p < 0.001$; Min: minutes; °C: degrees Celsius; %: percentage; Kcal/Kg: kilocalories/kilogram; ab: Means in the same column followed by different letters differ significantly at the 5% threshold; ND: Not Determined.

1) Moisture content of raw materials

Fresh orange and pineapple peels had significantly different moisture contents, 51.10% and 81.08% respectively ($p < 0.001$). These values are higher than that obtained for rice husks, which were already dry at the time of purchase (9.33%). The moisture content of fresh starch was 46.56% and lower than that of fresh orange and pineapple peels ($p < 0.001$). After drying, the opposite trend was observed; orange peels and rice husks had similar moisture contents (10.99% and 9.33%, respectively, $p > 0.05$) and lower than that of dried pineapple peels (12.47%; $p < 0.001$). The moisture content of starch decreased to 15.21% after drying ($p < 0.001$), but this value was significantly the highest of all values recorded after drying.

2) Ash content of raw materials

The ash content also varied from one raw material to another. Rice husks had the highest ash content ($p < 0.001$), at 18.85%. They were followed by pineapple peelings (9.45%) and orange peelings, which had similar levels (9.45% and 9.19%, respectively) ($p > 0.05$). Dry cassava starch had the lowest ash content (0.48%).

3) Temperature and time to reach flash point of raw materials

The flash point time and temperature, which indicate the flammability of the raw materials used, varied significantly overall ($p < 0.001$). Cassava starch had the highest flash point time (24.40 min) with the lowest flash point temperature overall (168.00°C). All other raw materials had similar flash point temperatures ($p > 0.05$) with different flash point times ($p < 0.001$). Orange peel had the highest temperature (224.00°C), while similar values were recorded for all other raw materials used ($p > 0.05$).

4) Gross lower calorific value and dry lower calorific value of raw materials

The gross and dry lower calorific values varied significantly from one raw material to another. Orange and pineapple peel had similar gross (2971.40 Kcal/kg and 2919.08 Kcal/kg, respectively) and dry (3500.93 Kcal/kg and 3532.07 Kcal/kg,

respectively) lower heating values ($p > 0.05$) and the highest overall. Rice husks had the lowest gross (2672.61 Kcal/kg) and dry (2900.73 Kcal/kg) calorific values ($p < 0.001$) overall.

3.2. Physicochemical Properties of Briquettes Made from Agricultural Residues

Table 3 shows the physicochemical characteristics of the different briquettes made from agricultural residues.

Table 3. Physicochemical properties of briquettes made from agricultural residues used for fish smoking (mean \pm standard deviation).

Parameters	BriqRi	BriqAn	BriqRiAn	BriqAnO	BriqRiAnO	Significance test
Moisture before drying (%)	43.23 \pm 4.39ab	43.33 \pm 3.42ab	45.38 \pm 3.48a	44.00 \pm 3.08ab	41.86 \pm 2.41b	*
Moisture after drying (%)	9.35 \pm 0.73d	10.74 \pm 0.39b	10.16 \pm 0.34c	12.03 \pm 0.37a	10.62 \pm 0.33b	***
Ash content (%)	14.32 \pm 1.16a	10.06 \pm 0.27b	6.79 \pm 0.38d	8.82 \pm 2.27c	8.48 \pm 0.15c	***
Flash point temperature ($^{\circ}$ C)	167.60 \pm 9.52cd	177.20 \pm 6.09b	162.80 \pm 1.09d	213.60 \pm 5.54a	171.60 \pm 3.84bc	***
Flash point time (Min)	24 \pm 4.58b	22 \pm 5.24b	15.80 \pm 1.92b	33.60 \pm 12.13a	16.40 \pm 2.30b	*
GLCV (Kcal/kg)	2872.25 \pm 58.12a	2590.75 \pm 31.80cd	2690.00 \pm 28.71b	2555.50 \pm 40.03d	2647.00 \pm 34.12bc	***
DLCV (Kcal/kg)	3220.47 \pm 53.31a	2948.42 \pm 41.85c	3008.36 \pm 17.71b	2910.61 \pm 29.83c	2904.92 \pm 17.60c	***
Shock rating	10.00 \pm 0.00a	9.80 \pm 0.44a	8.80 \pm 1.64ab	7.00 \pm 2.73b	8.80 \pm 1.64ab	NS
Shock resistance	Very good	Good	Good	Low	Good	

NS: Not significant, * $p < 0.05$; *** $p < 0.001$; Min: minutes; $^{\circ}$ C: degree Celsius; %: percentage; Kcal/Kg: kilocalories/kilogram; BriqRi: Briquette of ground Rice husks; BriqAn: Briquette of ground Pineapple peels; BriqRiAn: Briquette of ground Rice husks and ground Pineapple peels, BriqAnO: Briquette of ground Pineapple peels and ground Orange peels; BriqRiAnO: Briquette of ground Rice husks, ground Pineapple peels and ground Orange peels, GLCV: Gross Lower Calorific Value, DLCV: Dry Lower Calorific Value, ab: Means of the same line followed by different letters differ significantly at the 5% threshold.

1) Moisture content of briquettes

Immediately after manufacture, all five types of briquettes had moisture contents that were not significantly different, with the exception of BriqRiAnO briquettes, whose moisture content (41.86%) was lower than that of BriqRiAn (45.38%) ($p < 0.001$) but not different from those of BriqRi (43.23%), BriqAn (43.33%) and BriqAnO (44.00%) ($p > 0.05$). After drying, the briquettes had different moisture contents. BriqAnO had the highest moisture content (12.03%), followed by BriqRiAnO (10.62%) and BriqAn (10.74%), which had similar values ($p > 0.05$). BriqRiAn and BriqRi had the lowest moisture contents, but these were different ($p < 0.001$) (10.16% and 9.35%, respectively).

2) Ash content of briquettes

The highest ash contents were obtained in rice husk-based briquettes (BriqRi), (14.32%; $p < 0.001$). These were followed by pineapple-based briquettes (BriqAn), (10.06%; $p < 0.001$). Briquettes containing orange peel (BriqAnO: 8.82%; BriqRiAnO: 8.48%) had similar ash contents ($p > 0.05$). BriqRiAn briquettes had the lowest ash contents (6.79%; $p < 0.001$).

3) Temperature and time to reach the flash point of briquettes

In terms of flash point temperature, BriqAnO had the highest value (213.60°C) ($p < 0.001$); while BriqAn (177.20°C) and BriqRi (167.60°C) had the lowest and most similar values ($p > 0.05$). The value for BriqRiAn (162.80°C) was also not different from that of BriqRi ($p > 0.05$). As for flash point time, BriqAnO always had the highest value (33.60 min), followed by BriqRi (24.00 min) and BriqAn (22.00 min), whose values were similar ($p > 0.05$). BriqRiAn and BriqRiAnO also showed values that were not significantly different ($p > 0.05$), respectively 15.80 min and 16.40 min, and similar to that of BriqAn.

4) Gross lower calorific value and dry lower calorific value of briquettes

For lower calorific value, rice husk-based briquettes had the highest gross (2872.25 Kcal/kg) and dry (3220.47 Kcal/kg) lower calorific values, followed by BriqRiAn (2690.45 Kcal/kg and 3008.36 Kcal/kg). BriqAn (2590.75 Kcal/kg and 2948.42 Kcal/kg), BriqAnO (2555.50 Kcal/kg and 2910.61 Kcal/kg) and BriqRiAnO (2647.00 Kcal/kg and 2904.92 Kcal/kg) had the lowest gross and dry calorific values ($p < 0.001$).

5) Impact resistance (drop test)

For the impact resistance of the briquettes, the highest values ($p < 0.001$) were recorded for BriqRi, BriqAn, BriqRiAn, and BriqRiAnO briquettes (10.00, 9.80, 8.80, and 8.80, respectively). The lowest impact resistance of the briquettes was recorded for BriqAnO briquettes (7.00). The briquettes that showed very good impact resistance were BriqRi briquettes. Impact resistance was good for BriqAn, BriqRiAn, and BriqRiAnO briquettes. Overall, the briquettes with poor (low) resistance were BriqAnO briquettes.

4. Discussion

4.1. Characteristics of the Raw Materials: Rice Husks, Pineapple Peelings, Orange Peelings, and Cassava Starch

4.1.1. Moisture Content of Raw Materials

The high moisture content obtained for fresh pineapple peelings (81.08%) and orange peelings (51.10%) proves their high water content. They are therefore highly perishable and require immediate drying after collection. The moisture content of fresh pineapple peelings is close to the values obtained by [28] (85.60%) and lower than that (92.2%) reported by [29] in their respective studies on “Biomethanization of pineapple waste using efficient anaerobic consortia as a replacement for cow manure” and “Food uses of pineapple waste and by-products”. These differences may be due to the method of peeling the pineapple and/or to peelings from different varieties of pineapple produced in different areas (climatic

conditions and cultivation practices) [30] [31].

After drying, the moisture content recorded for all briquettes is below 15%, which is favorable for their use in briquette production. In general, the recommended moisture content of biomass for briquette production is between 5% and 15% [27]. The moisture content of orange peels (10.99%) was reduced to levels comparable to those of rice husks (9.33%), reflecting the effectiveness of the dehydration process. In contrast, pineapple peel retained a higher residual moisture content (12.47%), which can be explained by its fibrous structure and high water retention capacity. The low moisture content recorded for rice husks (9.33%) is well above that obtained by [32] (4.1%) for the same briquette.

As for cassava starch, although its initial moisture content (46.56%) was lower than that of the peelings, its moisture content after drying (15.21%) remained the highest. This finding can be explained by the hygroscopic capacity of starch, which makes it more difficult to dry.

4.1.2. Ash Content of Raw Materials

The ash content, an indicator of the mineral load of the materials, also varied significantly ($p < 0.001$). Pineapple and orange peel showed moderate and comparable ash contents (around 9%), while dry cassava starch had the lowest value (0.48%), reflecting its high degree of purification. This low content could make starch attractive for applications requiring a low mineral load, but its low calorific value limits its energy potential. Ash content has a significant influence on heat transfer at the fuel surface as well as on oxygen diffusion at the fuel surface during combustion [6] [33] [34]. In the present study, rice husks had the highest ash content (18.85%), which was higher than the content (16.96%) obtained by [35] in their study on the effectiveness of rice husk powder and ash against two insect pests, *Sitophilus zeamais* (Motsch) and *Tribolium castaneum* (Herbst), in stored rice in Senegal. The high ash content of rice husks could be attributed to their highly siliceous outer shell. [6] [35] [36] have pointed out that the high ash content of rice husks is due to the presence of silica oxides, which have significant thermal stability and resistance to oxidation during the pyrolysis process. This generates more ash after combustion. However, this high ash content limits their energy value, as a high mineral load is often associated with greater residue production after combustion.

Pineapple peel and orange peel had moderate and similar ash contents (around 9%). This value is higher than those reported (8.08% to 4.54%) by [23] for pineapple peel and orange peel, respectively. Dry cassava starch, on the other hand, had the lowest value (0.48%), indicating its high degree of purification. This low content could make starch attractive for applications requiring a low mineral load, but its low calorific value limits its energy potential. Low-ash biomass fuels are better suited for thermal use than high-ash fuels [33] [37].

4.1.3. Temperature and Time to Reach Flash Point of Raw Materials

Flammability varied depending on the raw material, with a higher temperature of

224 °C in 7.2 minutes for orange peel, suggesting better thermal stability before ignition, and a lower temperature of 168 °C coupled with a longer flash point time (4 minutes) for dry cassava starch. These values are comparable to those reported by [38], who showed that tropical biomasses rich in volatile compounds generally have higher flash point temperatures. The other briquettes had similar flash point temperatures ($p > 0.05$), but with significant differences in time, which could reflect differences in density or fine organic composition.

The variation in flash point temperatures and times recorded between rice husks, pineapple peelings, orange peelings, and cassava starch can be explained by their differences in chemical composition, volatile matter content, and moisture content. Furthermore, in this work, the use of non-carbonized agricultural residues, rich in volatile matter, is consistent with the results of [36] [39] [40], who showed that charcoal, which has undergone carbonization, has a much lower volatile matter content than green charcoal, which retains a greater proportion of volatile matter. Thus, the chemical nature (cellulose, lignin, sugars, oils), moisture content, and physical structure of biomasses strongly influence their thermal behavior [36] [41] [42].

4.1.4. Gross Lower Calorific Value and Dry Lower Calorific Value of Raw Materials

The highest lower calorific values, both in their raw and dry states, were obtained from orange and pineapple peelings. This makes them potential candidates for energy recovery. On the other hand, rice husks, despite their low moisture content, have lower calorific values (2672.61 Kcal/kg in raw form), probably due to their high ash content and more rigid lignocellulosic structure. The values obtained overall are similar to those of [32], who obtained 2938.86 Kcal/kg to 3227.78 Kcal/kg for the lower calorific value of the corn cob, sawdust, and rice husk samples. The calorific value of the samples analyzed in this study was higher than that reported by [23] for pineapple and orange peels, which yielded the same values (2959.59 Kcal/kg), and lower than that reported by [43] for rice husks (3410 kcal/kg) in their research. [41] demonstrated that materials rich in fiber and simple sugars have a higher PCI. However, [42] demonstrated that fruit peels contain considerable amounts of sugars, cellulose, pectin and hemicellulose, ash, and moisture. Calorific value significantly influences energy density, which is a factor to be taken into account when combining one or more residues during agglomeration, as it allows the density of the briquettes to be standardized [44].

The results obtained for the physicochemical parameters of the rice husks, pineapple peelings, and orange peelings studied confirm the findings of certain authors [6] [23] [27] [29]-[31] [42] [43] [45] that agricultural residues can be used as briquettes to produce renewable energy sources. Overall, the results reveal a high energy potential for fruit peels, particularly orange and pineapple peels, which combine good drying properties, low ash content, and high calorific value. In contrast, rice husks, despite their availability, appear to be less efficient from an energy standpoint due to their high ash content.

4.2. Characteristics of Briquettes Crafted from Agricultural Residues

4.2.1. Moisture Content of Briquettes

The results of the analyses carried out on the briquettes show that all briquettes initially had similar moisture contents (43% - 45%) except for BriqRiAnO (41.86%). After drying, these levels diverged significantly: BriqAnO retained the highest moisture content (12.03%), while BriqRi (9.35%) remained the driest, followed by BriqRiAn (10.16%) and BriqAn (10.74%). According to [46], moisture must be $\leq 10\%$ to ensure combustion efficiency and minimize excessive steam and smoke emissions. BriqAnO (12%) and BriqRiAnO (10.62%) therefore had moisture content levels above the recommended standard and problems with durability, density, and ease of combustion (less efficient if water absorbs thermal energy) could arise with these briquettes. Excessive moisture can reduce energy efficiency and promote microbial degradation or self-ignition under certain conditions.

The low moisture content obtained before drying BriqRiAnO briquettes (41.86%) is lower than that reported by [47] (48.89%) for ecological charcoal based on *Prosopis juliflora* bound to *Eichhornia Crassipes* before drying. It was found that rice husks and rice husk-based briquettes had similar (9.33% and 9.35%) and the lowest moisture content after drying. This finding was made by [15] for rice husk briquettes manufactured in the same way, except that in their study the briquettes were compacted manually, whereas here they were compacted using a hydraulic press. The value of 9.35% obtained for rice husk briquettes is between the values obtained by [34] on the moisture content (5.76% to 12.09%) of briquettes made from a mixture of rice husks and sawdust and is lower than those obtained (14.29% to 16.33%) by [48] on rice husk briquettes after carbonization.

The difference in the trend observed in moisture content before and after drying the briquettes indicates that the rate of water release during drying is not the same for all types of briquettes. The hydrophilic affinity of cassava starch accentuates this phenomenon, and the structure of the initial briquettes also influences the speed of the drying process, even after the same exposure time to drying [6] [34] [49]-[52].

4.2.2. Ash Content of Briquettes

BriqRi briquettes had the highest content (14.32%), followed by BriqAn (10.06%), BriqAnO (8.82%), and BriqRiAnO (8.48%), while BriqRiAn came in last with the lowest content (6.79%).

The high ash content of rice husks has already been reported by [46], who indicated rates of 10% - 16% for this type of biomass. As for [53], a range of 15% - 20% was reported as the average ash content of rice husk briquettes. The EN ISO 17225-6 standard recommended an ash content of between 1% and 3% for biomass briquettes, while specifying that lower values are preferable for better combustion and reduced residues. According to [46], briquettes with an ash content of $< 4\%$ are preferred according to standards to reduce furnace fouling

and equipment corrosion. None of the briquettes produced in this study met the standard requirements in terms of ash content, except potentially BriqRiAn (6.79%, still above 4%). These drops in ash mass in briquettes compared to briquettes result from a dilution of the briquette masses in the briquettes. The combination of rice husk and pineapple (BriqRiAn) is an effective option for reducing ash content.

A negative correlation was found between the moisture content and ash content of the briquettes. The ash content increases with low moisture content. For example, the moisture content of rice husk briquettes is the lowest, while these same briquettes have the highest ash content. This finding confirms the conclusion of [48] that the lower the moisture content of the briquettes, the higher the ash content, reflecting complete combustion of the organic matter.

It was also found that, for equal weight, the ash content of a briquette is lower than that of the briquette from which it was made. This finding can be explained by the use of starch paste as a binder during the manufacture of briquettes, leading to a reduction in the proportion of briquette used to manufacture a briquette of the same weight as the briquette.

[36] obtained a very slight decrease in the ash content (47% to 44%) of rice husk biochar briquettes produced when binders based on cassava, matooke, and sweet potato peelings were added. The ash contents obtained in the study for the briquettes are lower than those reported (33.82% to 58%) by [6] for briquettes with a high binder content and higher than those reported by [54] for briquettes bound with gum arabic (1.36%) and those bound with starch (2.84%).

Ash content directly influences the combustion quality of briquettes. Complete combustion produces mainly CO₂, water vapor, and ash, the quantity of which depends on the non-volatile minerals contained in the organic matter used for the test sample. This hot ash resulting from the combustion of organic matter promotes, through radiation, a more uniform emission of heat energy without PAH emissions, while influencing the smoke profile and organoleptic quality of smoked fish [11] [12] [55] [56]. On the other hand, incomplete combustion generates carbon sawdust, CO, and a large number of PAHs, which impact the chemical quality of smoked fish. At the same time, carbon sawdust blackens smokehouses, racks, and smoked fish, impairing their health and marketability.

4.2.3. Temperature and Time to Reach the Flash Point of Briquettes

The high values observed for BriqAnO (213.6°C and 33.6 min) can be explained by the higher moisture content of this briquette. They indicate slow ignition and therefore thermal stability beneficial for storage in hot or humid environments, thus reducing the risk of self-ignition. However, the excessively high flash point can make ignition more difficult, thereby requiring the use of combustible initiation materials.

Briquettes containing rice husks provided low flash points with the highest ash content, indicating lower thermal efficiency and making them less suitable for energy use compared to other types of briquettes. Finally, the results are consistent

with the conclusions of [57], according to which briquettes made from rice husk biochar require higher flame temperatures to achieve effective ignition.

4.2.4. Gross Lower Calorific Value and Dry Lower Calorific Value of Briquettes

The gross and dry lower calorific values obtained in the study range from 2555.50 kcal/kg to 3220.47 kcal/kg. These values indicate good energy potential, especially for rice husk briquettes, whose dry lower calorific values are around 3220 kcal/kg, or 13.5 MJ/kg. This level is consistent with those expected for well-dried rice husk briquettes, 13.8 to 15.1 MJ/kg [53].

[46] reported NCVs of 17 - 18 MJ/kg for rice husk briquettes after optimal drying. The rice husk briquettes in the study have good energy performance. However, the high ash content and high moisture content (>5%) combined may limit the net usable energy and reduce the actual efficiency during combustion. The PCI values in the study are lower than the average calorific values obtained by [48] for charcoal (6700 Kcal/kg) and firewood (4350 Kcal/kg). [15] found values of 2887.68 to 3450.38 Kcal/kg for these same briquettes.

4.2.5. Impact Resistance (Drop Test)

The results of the impact resistance test reveal that BriqRi briquettes (10) have very good impact resistance and that all briquettes containing rice husks have good resistance. This is consistent with the observations of [27] on manually manufactured rice husk briquettes and those of [34], who evaluated the performance of an improved stove using rice husks mixed with sawdust. It appears that the variation in the impact resistance of briquettes depends heavily on the composition of the briquettes, the binder used, the internal structure, and the manufacturing process [27] [34] [51] [58]. The high strength of BriqRi (10) and mixtures such as BriqRiAn (8.8) is consistent with high-density briquettes made from resistant fibers [59] [60].

In contrast, BriqAnO with a strength of 7 probably suffers from insufficient cohesion, likely due to excessive moisture or the absence of an adequate binder. Additives with natural binders other than cassava starch (cornstarch, gum arabic, and clay) could improve durability while controlling ash content.

In summary, BriqRi and BriqRiAn, and BriqRiAnO briquettes with their relatively acceptable flash point (167.60°C, 162.80°C and 171.60°C), their slow combustion (24 min, 15 min and 16 min), and their ash content (14.32%, 6.79% and 8.48%) would be ideal for optimal heat energy production. To this could be added the possible natural aromatization of the products smoked by these briquettes due to the orange peels which can give a light fruity smoke, favorable to the smoking of fish, poultry or cheese. An improvement in the formulation of the components of these briquettes or better drying can be considered in the direction of reducing their humidity and strengthening their mechanical resistance. As for the briquettes, they would be a good compromise between aroma, stability and solidity, due to their good mechanical resistance, their moderate ash content. Rice-based

briquettes (BriqRi) and rice-pineapple-based briquettes (BriqRiAn) are highly recommended because the former are high in ash and could maintain heat energy production without PAH emissions, with their low flash point, will ignite very quickly. Adjustments in terms of binders, drying, or combination of briquettes could improve their performance so that they are suitable for food smoking.

Furthermore, the combustion of organic matter at a relatively low temperature can generate polycyclic aromatic hydrocarbons (PAHs). The toxicological effects of all PAHs are not fully known, but some can cause systemic, reproductive, genotoxic and/or carcinogenic effects [61]. Regulations strictly limit the presence of benzo[a]pyrene (BaP), which represents approximately 58% of the carcinogenic risk of PAHs, between 2 - 5 µg/kg of smoked fish [62]-[65]. Similarly, the total PAH content must not exceed 12 µg/kg according to [62] [63] [65]. Studies by [15] on the chemical quality of fish smoked with agricultural residue briquettes revealed that the lowest PAH concentrations in smoked fish were obtained with rice husk briquettes (BriqRi), while those smoked with pineapple peel briquettes (BriqAn) had the highest levels for the majority of PAHs. Similarly, the search for BaP in the smoked fish samples analyzed by the authors led to an indeterminacy. Also, the study suggested that to reduce exposure to PAHs, consumers should remove the skin from smoked fish before consumption, as the latter often concentrates these compounds. However, it is noted that the routes and duration of exposure to PAHs strongly influence the level of contamination of target groups. These routes include ingestion (consumption of smoked fish), inhalation (combustion fumes), and dermal contact (handling smoked products). While in our case, the oral route is the main source of contamination for the end consumer, for processors, all routes of contamination are possible. In light of all the above, the briquette most suitable for use as fuel in fish smoking would be the one that generates the fewest PAHs for health and environmental reasons.

5. Conclusion

The study characterized the physical and energetic performances of briquettes formulated from rice husks, pineapple peels and orange peels. The results highlighted a marked difference between the types of briquettes. BriqRi briquettes had the best calorific values and a high ash content capable of maintaining fish smoking without PAH emissions after the disappearance of organic matter. Conversely, while BriqAnO briquettes showed excellent thermal behavior (high flash point and slow combustion), they have low mechanical resistance and generate a lot of PAHs. BriqRiAnO composite briquettes offered an optimal balance between thermal performance, low ash content and good impact resistance, but high total PAH contents, which put them out of the category compared to BriqRi briquettes and therefore poor candidates for food smoking applications. Optimizing the drying process and the binder used without increasing the ash content could improve the stability and strength of most briquettes. Carrying out additional analyses, such as evaluating the technological and health qualities of fish or other foods smoked

with each briquette, will allow for a complete description of the profile of each briquette. Also, an assessment of the techno-economic viability of these briquettes will allow for the practical interest of briquettes compared to traditional fuels.

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Contributions of Authors

C. F. A. S. drafted the experimental plan, supervised data collection, and edited the article.

K. A. I. G. collected the data and proposed the first draft of the article.

S. P. K. analyzed the data.

A. N. M. G. contributed to the flash point tests carried out on the briquettes and corrected the article.

E. G. D., H. G. M. T., E. E. C. E. S., and C. G. O. contributed to the manufacture of the briquettes and the collection of data.

D. S. D., L. B-M., and I. Y. A. K. contributed to the validation of the experimental design and the correction of the article.

All authors contributed to this scientific and intellectual work and gave their consent for its publication.

Conflicts of Interest

The authors declare that they have no financial interests or personal relationships that could have influenced the work presented in this article.

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