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Analysis of binder proportions on the calorific value in a briquette made from cocoa pod husk in the Peruvian Amazon

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Introduction: The growing global demand for fuel has created challenges in the supply of raw materials, positioning biomass derived from cocoa pod husk waste as an economically viable and environmentally sustainable energy alternative.
Methods: This study evaluated the effect of different binder types on the calorific value of briquettes produced from fermented cocoa pod husk waste in the Peruvian Amazon. For the calorific value assay, 1.05 kg of fermented cocoa pod husk waste was combined with 100 g of starch-based binders derived from corn, cassava, or potato, all sourced from the San Martín region. Statistical analyses were performed in R Studio using the dplyr package, and mean comparisons were conducted with Tukey's HSD test ($p < 0.05$).
Results: The lowest ash content was obtained with the potato-starch binder (7.03%), whereas the highest value was recorded in the control treatment without binder (8.71%). Fixed carbon content ranged from 3.70% to 5.97% across treatments. The lowest calorific value was observed with the corn-starch binder (3,486.0 kcal/kg), while the highest was achieved with cassava starch (3,586.66 kcal/kg).
Discussion: These findings demonstrate the technical feasibility of producing high-quality charcoal briquettes from cocoa pod husk waste using starch-based binders, providing a sustainable alternative to conventional fuels.

KEYWORDS

calorific value, circular economy, elemental composition, combustion, gravimetry

1 Introduction

Plant biomass represents a viable alternative to replace fossil and conventional fuels for cooking in developing countries such as Peru, offering multiple benefits including the reduction of greenhouse gas emissions. Consequently, the use of plant biomass is increasingly recognized as a sustainable strategy to meet global energy demand while improving quality of life (Bot et al., 2022; Akam et al., 2024). Biomass resources are promoted for their availability, low cost, purity, and environmental compatibility (Alruqi and Sharma, 2023).

In the Peruvian Amazon, cocoa (*Theobroma cacao* L.) is one of the most economically important crops, with the San Martín region being the leading producer, accounting for approximately 37.5% of national output (Ministry of Agriculture and Irrigation (MINAGRI, 2019), supported by soils and microbiota favorable for crop growth (Vallejos-Torres et al., 2021; Vallejos-Torres et al., 2022). Nationwide, cocoa is cultivated mainly in the departments of San Martín, Junín, Cusco, Ucayali, Huánuco, Ayacucho, and Amazonas, which together represent about 96% of national production, yielding 153,000 tons from 146,800 ha (Cayetano et al., 2021). The commercial product is the seed, which constitutes only about 10% of the total fruit biomass; the remaining 90% is discarded as waste (Loor, 2020). Among this residual biomass, the cocoa pod husk is a significant resource that remains largely underutilized.

The growing global demand for renewable energy, coupled with the urgent need to manage agro-industrial waste such as cocoa pod husk, has driven the search for sustainable alternatives for solid biofuel production (Sharma et al., 2022). In cocoa-producing regions such as the Peruvian Amazon, cocoa pod husk—a plentiful but underutilized by-product—offers significant potential as a feedstock for bioenergy (Santos et al., 2024). However, to ensure its technical and economic viability as a fuel, it is essential to optimize transformation processes, particularly the selection and dosage of binders, which directly influence critical properties such as calorific value, durability, and combustion efficiency of briquettes (Mamudu et al., 2023).

Although previous studies have explored residual biomass for biofuel production, few have focused specifically on cocoa pod husk, and even fewer have systematically assessed the effect of locally sourced binders on its energy properties (Mustafa and Ibrahim, 2023; Akam et al., 2024). In the Amazonian context, scientific information is scarce regarding the influence of starch-based binders—such as cassava, potato, and corn starch—on key parameters including ash content, fixed carbon, and calorific value of briquettes (Harussani et al., 2025). This study addresses this knowledge gap through a systematic experimental approach to determine the optimal combination of fermented cocoa pod husk and local binders for high-quality biofuel production.

Cocoa pod husks, due to their high lignin, cellulose, and hemicellulose content (Djali et al., 2021), are difficult to degrade and are often discarded in fields, promoting the growth of pathogenic microorganisms. This waste stream highlights the need for sustainable management strategies that valorize agricultural by-products, reducing environmental pollution while generating value-added products (Herrera-Rengifo et al., 2020). Briquettes, composed of uniform biomass particles compacted under pressure, are widely used as bioenergy sources in rural and agricultural areas because they enable controlled combustion (Oladosu et al., 2023) and foster circular economy practices that reduce environmental impact (Ashokkumar et al., 2022). The addition of suitable binders is critical to improve cohesion, compression strength, and combustion performance.

Globally, it is estimated that by 2030, about one billion people in developing economies will still rely on raw biomass for cooking without access to clean cooking facilities (Röder et al., 2022). Briquettes from agricultural residues—such as coconut shells with cassava (*Manihot esculenta* Crantz) binder (Hoyos et al., 2019), rice (*Oryza sativa* L) husks (Lubwama et al., 2018), banana *(Musa paradisiaca* L) peels (Bot et al., 2023), or corn (*Zea mays* L.) straw with cassava binder (Tarka et al., 2023)—offer an economical and renewable energy alternative (Nwankwo et al., 2023; Adeleke et al., 2022).

Despite advances in biomass briquetting, studies on cocoa pod husk briquettes in Peru are lacking. At the National Institute of Agrarian Innovation (INIA), cocoa pod husks are currently valorized through solid fermentation to produce liquid biofertilizers, leaving behind nutrient-depleted fermented cocoa pod husks with sufficient biomass for energy applications.

Therefore, the objective of this research was to evaluate the effect of three starch-based binders—cassava, corn, and potato (*Solanum tuberosum* L.)—on the calorific value and combustion-related properties of fermented cocoa pod husk briquettes. The findings will inform the selection of optimal binder types for maximizing briquette quality, providing a replicable framework for addressing energy poverty with low-cost, locally available inputs.

2 Materials and methods

2.1 Location of the experimental area

The study was carried out in the Soil, Water and Foliar Laboratory (LABSAF) and greenhouse of the Agricultural Experiment Station EL Porvenir (South Latitude: 06° 35′50“West Longitude: 76° 19′30”), of the National Institute of Agrarian Innovation (INIA), located in the district of Juan Guerra, province and department of San Martin, Peru. The average temperature was 17°C–35°C and rainfall was 1,000–1,500 mm per year.

2.2 Description and origin of cocoa pod husk

Cocoa pod husks from the Colección Castro Naranjal 51 (CCN-51) variety, obtained from productive plants, were sourced from farms in Tocache, San Martín Region, Peru (Figure 1a). CCN-51 originates from the cross ICS-95 × IMC-67, subsequently crossed with a native clone from eastern Ecuador known as “Canelos.” The fruit is characterized by a reddish-violet color, oblong shape, and pronounced surface rugosity (García, 2010). The characteristics of cocoa beans are strongly influenced by factors such as climate, origin, processing methods, and plant genotype (Betancourt-Sambony et al., 2025).

A total of 1.05 kg of fresh cocoa pod husk residues (Figure 1c), previously subjected to decomposition after liquid biofertilizer extraction at the El Porvenir Experimental Agricultural Station (INIA, San Martín), were mixed with 100 g of binder—either corn, cassava, or potato starch—at a ratio of 9.5:1 (biomass: binder). This proportion was determined in preliminary cohesion tests. The mixtures were homogenized manually for 15 min until a uniform consistency was achieved. The husks were initially chopped to 1.5–2.0 cm pieces, yielding 12.6 kg of fresh biomass (Figure 1d), and placed on mats under a protective cover for natural decomposition. Turning was performed every 7 days for 60 days under ambient conditions to ensure uniform breakdown (Figure 1e). The decomposed cocoa pod husk was then used to

FIGURE 1
Briquette production from cocoa pod husks collected in established field plantations: **(a)** cocoa plant in production, **(b)** fresh cocoa beans, **(c)** cocoa pod husk crushing, **(d)** cocoa pod husk decomposition, **(e)** briquette manufacturing, and **(f)** briquettes produced with cassava, corn, and potato binders.

produce briquettes with a mechanical press (Figure 1f). Compaction was carried out in a manual briquetting device with a 15 cm diameter piston, applying approximately 50 kgf/cm^2 of pressure (calculated from a 64 kg force applied via a 50 cm lever arm). Each briquette had standardized dimensions of 15 cm in diameter × 12 cm in height and an approximate weight of 1.15 kg. Drying was performed under sunlight for 72 h until the residual moisture was below 10%.

Combustion and elemental composition parameters were determined according to the following standards: ASTM D3172 (proximate analysis: moisture, volatiles, ash, and fixed carbon), ASTM D5865 (higher heating value using a bomb calorimeter), ASTM D4239 (sulfur content via Eschka method), ASTM D5373 (carbon, hydrogen, and nitrogen content by elemental combustion), and ISO 18847 (bulk density by gravimetric method).

2.3 Binder types and experimental treatments

Three starch-based binders—corn, cassava, and potato—were selected due to their frequent use in briquetting, proven effectiveness, and local availability (Lubwama et al., 2024). In addition, a control treatment without binder was included. This resulted in a total of four treatments, each with three replicates, for a total of twelve experimental units (EUs). Each EU consisted of a single briquette produced according to the procedure described in Section 2.4 (Manufacture of briquettes).

2.4 Manufacture of briquettes

For briquette production, 1.05 kg of fermented cocoa pod husk residue from the biofertilizer processing stage was mixed with 100 g of binder—corn, cassava, or potato) starch—until a homogeneous mixture was obtained. The mixture was then compacted using a manual briquetting press and sun-dried until the moisture was below 10%. This process was repeated for each experimental unit according to the treatment design.

The briquettes were analyzed for proximate composition, ultimate composition, density, and calorific value. Parameters included moisture, volatile matter, ash content, fixed carbon, bulk density, elemental carbon, hydrogen, oxygen, nitrogen, sulfur, and higher heating value. Analyses were performed following standard test methods, including ASTM D3172 (proximate analysis), ASTM D3175 (volatile matter), ASTM D5865 (higher heating value), ASTM D4239 (sulfur by Eschka method), ASTM D5373 (ultimate analysis: C, H, N), and ISO 18847 (bulk density by gravimetry) (Kebede et al., 2022; ASTM, 2018).

2.5 Data analysis method

Statistical analyses and data visualization were performed using R software (R Core Team, 2023). The packages dplyr were used for efficient data manipulation (Wickham et al., 2023) and ggplot2 for generating clear and reproducible statistical visualizations (Wickham, 2016). Prior to inferential testing, the assumptions of residual normality and homogeneity of variances across treatments were verified to determine the appropriateness of parametric statistical methods or, if necessary, the application of data transformations or non-parametric alternatives. Normality was assessed using the Shapiro–Wilk test ($p < 0.05$), selected for its high power and sensitivity in detecting deviations from normality, particularly in small to moderate samples (Razali and Wah, 2011), outperforming tests such as Kolmogorov–Smirnov or Anderson–Darling. Homogeneity of variances was evaluated using Levene's test ($p < 0.05$), which is robust to non-normal data, unlike Bartlett's test, which is highly sensitive to such deviations (Brown and Forsythe, 1974).

Differences among treatment means were analyzed using Tukey's Honest Significant Difference (HSD) test ($p < 0.05$) implemented in the agricolae package (De Mendiburu, 2010). The dataset was organized into five main categories: elemental composition, combustion parameters, gravimetric properties, volatile matter, and calorific value. For visualization, multiple plot types were generated, including boxplots with mean indicators,

TABLE 1 Bidirectional F-values and probability (p-values) examining the effects of binder proportions on the gravimetric assessment, volatile matter content, and calorific value of briquettes made from cacao pod husk.

Treatment	H° (%)	AD g/cm3	V (%)	Ce (%)	FC (%)	HV (kcal/kg)
F	1,523,289	275.73	112,927	8,386.81	44,866.5	63,735,813
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
R^2	1	0.99	1	1	1	1
C. V.	0.01	0.71	0.05	0.19	0.22	4.30E-04

Means joined by the same letter mean statistically similar averages at 95% confidence intervals according to Duncan's test. Abbreviations: H°, moisture; DA, bulk density; V, volatile; Ce, ash; FC, fixed carbon; and HV, calorific value.

bar charts with standard error bars, and "bubble jitter" scatter plots, which allowed clear representation of data variability among treatments with different binder types. These graphical representations facilitated both exploratory and comparative interpretation of the evaluated indicators, supporting the ANOVA-based statistical analysis and mean comparisons.

3 Results and discussion

3.1 Physic properties of the binder

The analysis of variance revealed a statistically significant effect of treatment ($p < 0.0001$), indicating that moisture, bulk density, volatile matter, ash, and fixed carbon varied according to binder type. The model exhibited an $R^2 \geq 99\%$, indicating high explanatory power (Table 1).

Bulk density differed significantly among binder types (Figure 2a; Table 2). The lowest values were recorded in the treatments without binder and with potato binder (0.76 g/cm^3), whereas the highest was observed in the corn binder treatment (0.85 g/cm^3). For comparison, Nonsawang et al. (2024) reported a bulk density of 0.51 g/cm^3 for cassava tuber powders. Bulk density is a critical parameter for assessing combustion properties and the flammability of biomass briquettes (Rajkumar and Venkatachalam, 2013). According to Aransiola et al. (2019), briquettes produced from cassava and corn starch possess densities suitable for producing stable, easy-to-store fuels, with shelf life remaining acceptable after several months of storage. Similarly, Sen et al. (2016) reported densities ranging from 0.40 to 0.90 g/cm^3 for briquettes produced from cassava rhizomes. Bulk density can be significantly affected by process variables, particularly binder moisture (Dinesha et al., 2019; Bency et al., 2023), which represents the total water present in the briquette.

The moisture of the briquettes ranged from 44.49% to 55.37%, showing significant differences among treatments (Figure 2b; Table 2). The lowest value was recorded in the treatment without binder, whereas the highest was observed in the potato binder treatment. According to Aransiola et al. (2019), moisture in briquettes produced from corn starch ranged from 4.68% to 7.09%, while those from cassava starch ranged from 4.43% to 6.06%. In the present study, the moisture values were substantially higher than those reported by these authors. This difference could be attributed to the hygroscopic nature of the carbonized corn, cassava, and potato materials used, as well as to the greater water availability in binders with higher concentrations. Potato binder briquettes exhibited a slight increase in moisture and, consequently, a marginally lower calorific value (Souček and Jasinskas, 2020). In addition, Lubwama et al. (2024) reported a particle density of 0.45 g/cm^3 for rice husk briquettes with potato binder—lower than the values observed in this study—and a moisture of approximately 30% for the same binder type.

In this study, binders were dried under ambient conditions, and the high external humidity typical of the Amazon rainforest likely contributed to the elevated moisture levels compared with other reports. This could be explained by the hygroscopic properties of the carbonized maize, cassava, and potato materials, combined with the water retained in binders of increasing concentration (Aransiola et al., 2019). Furthermore, drying under humid ambient conditions, without the use of mechanical dryers, may have further increased the final moisture of the binders.

3.2 Chemical properties of the binder

The ash content of the binders varied significantly among the different types (Figure 3a; Table 2). The lowest value was recorded for the potato binder treatment, averaging 7.03%, whereas the highest was obtained in the binderless treatment, with an average of 8.71%. Nonsawang et al. (2024) reported ash contents ranging from 0.08% to 7.62%, similar to the averages obtained in this study. Likewise, the ash content of charcoal and binders has been reported to vary from 2.52% to 10.93%, while in the present study it ranged between 7.03% and 8.71%. These values comply with EN 1860-2:2023 for charcoal briquettes, which specifies an ash content not exceeding 18%. Variations in ash content can affect both calorific value and thermal efficiency; high ash levels in charred fuel reduce thermal conductivity and oxygen diffusivity, thereby lowering combustion efficiency (Ruiz-Aquino et al., 2019).

The fixed carbon content of the binders ranged from 3.70% to 5.97%, with significant differences, the highest being recorded for the binderless treatment (Figure 3b; Table 2). In comparison, Nonsawang et al. (2024) obtained 13.30% fixed carbon with cassava tuber binder. The fixed carbon content in the charcoal powder of this study did not exceed the EN 1860–2:2023 requirement

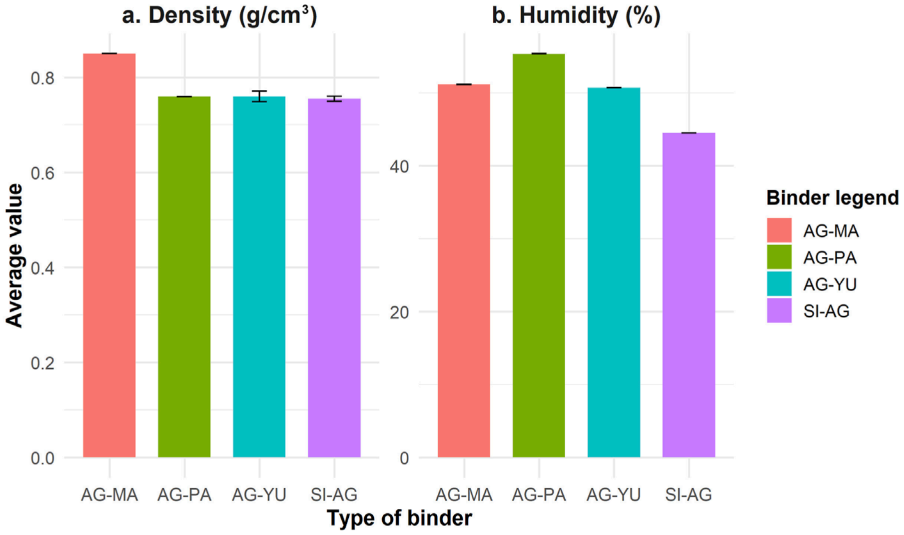

FIGURE 2
Characteristics of cocoa pod husk briquettes produced with cassava, corn, and potato binders: **(a)** briquette density and **(b)** briquette moisture. Abbreviations: AG-MA, corn binder; AG-PA, potato binder; AG-YU, cassava binder; and SI-AG, no binder.

TABLE 2 Gravimetric assessment, volatile matter content, and calorific value of a briquette made from cacao husk.

Traitements		H° (%)	DA g/cm3	V (%)	Ce (%)	FC (%)	HV (kcal/kg)
Without binder	Avg	44.49	0.76	40.84	8.71	5.97	3,586.66
	SD	0.01	0.01	0.00	0.01	0.01	0.01
	Group	a	b	d	d	d	c
Corn starch	Avg	51.15	0.85	37.44	7.71	3.70	3,486.00
	SD	0.01	0.00	0.03	0.01	0.01	0.02
	Group	c	a	b	b	a	a
Cassava starch	Avg	50.72	0.76	37.48	7.95	3.85	3,617.62
	SD	0.01	0.01	0.01	0.02	0.01	0.02
	Group	b	b	c	c	b	d
Potato starch	Avg	55.37	0.76	32.89	7.03	4.72	3,517.97
	SD	0.01	0.00	0.02	0.02	0.02	0.01
	Group	d	b	a	a	c	b

Averages joined by the same letter mean statistically similar averages at 95% confidence intervals according to Duncan's test. Abbreviations: H°, moisture; DA, bulk density; V, volatile; Ce, ash; FC, fixed carbon; and HV, calorific value.

(>60% dry basis). Fixed carbon was not a decisive parameter for thermal properties in this study, as lower fixed carbon generally corresponds to a lower calorific value. According to Ossei-Bremang et al. (2023), fuels with higher fixed carbon content tend to have higher calorific values. Furthermore, significant fixed carbon levels in feedstocks indicate potential for thermochemical conversion into biochar for briquette production (Foong et al., 2020).

The volatile matter of the binder powder ranged from 32.89% for the potato binder to 40.84% for the binderless treatment, with significant differences among treatments (Figure 3c; Table 2). Nonsawang et al. (2024) reported values ranging from 8.82% to 95.60%, with coconut husk showing 23.62%. Owino et al. (2024) found volatile matter between 21.1% and 36.2%, whereas in the present study it ranged from 32.89% to 40.84%. The relatively low volatile matter

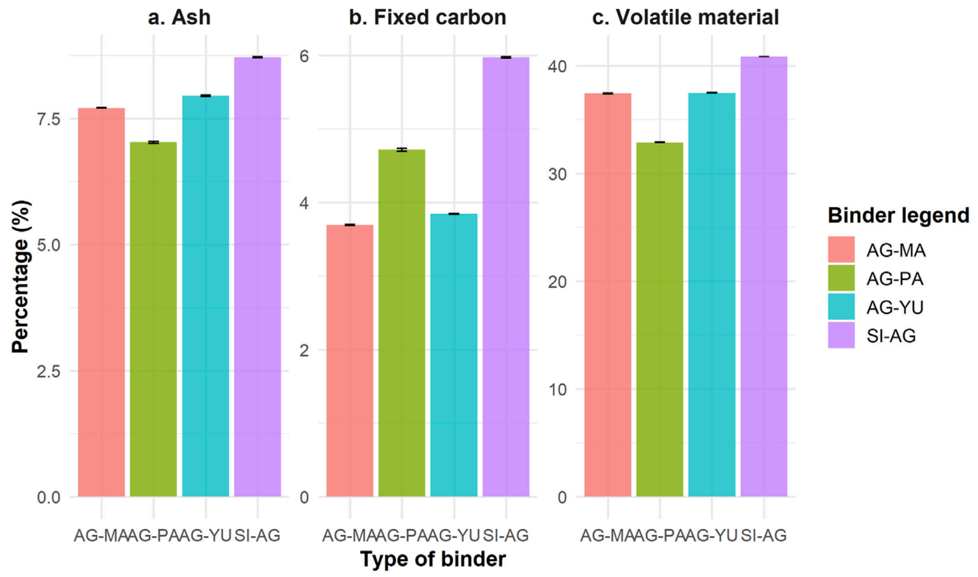

FIGURE 3
Proximate analysis of briquettes: **(a)** ash content, **(b)** fixed carbon content, and **(c)** volatile matter content. Abbreviations: AG-MA, corn binder; AG-PA, potato binder; AG-YU, cassava binder; and SI-AG without binder.

TABLE 3 Bidirectional F-values and probability (p-values) examining the effects of binder proportions on the composition and combustion analysis of briquettes made from cacao pod husk.

Treatment	C (%)	H (%)	N (%)	O (%)	S (%)
F	202,962	916.5	273.55	27,823.4	11
p-value	<0.0001	<0.0001	<0.0001	<0.0001	0.0023
R^2	1	1	0.99	1	0.8
C. V.	0.01	0.18	0.49	0.04	7.96

Means followed by the same letter are not significantly different at the 95% confidence level according to Duncan's test. Abbreviations: C, carbon; H, hydrogen; N, nitrogen; O, oxygen; S, sulfur.

was influenced by the carbonization process (Shiferaw et al., 2017). Excessive binder content could have adverse health implications due to increased smoke emissions during the initial combustion stage.

3.3 Elemental composition analysis and calorific value of briquettes

The analysis of variance showed that the treatments exerted a statistically significant effect on the carbon, hydrogen, nitrogen, and oxygen contents ($p < 0.0001$). The model yielded an R^2 value ≥99%, indicating a high explanatory power (Table 3). Sulfur content ($p = 0.0023$) also varied significantly, depending on the type of binder applied.

The carbon content ranged from 35.95% to 38.76%, with the highest value recorded in the corn binder treatment and the lowest in potato binder treatment, both differing significantly (Figure 4a; Table 4). These values were inferior to those reported by Mekonen et al. (2024), who obtained an average carbon content of 47.49% in briquettes made from sugarcane bagasse, and lower than the range of 41.42%–83.71% reported by Nonsawang et al. (2024) for charcoil briquettes produced from agro-industrial feedstocks with cassava-based binders.

Hydrogen content varied between 5.19% and 5.53%, with significant differences among treatments; the highest value was observed in the corn binder treatment (Figure 4b; Table 4). These results fall within the range reported by Nonsawang et al. (2024) (3.06%–7.80%). Similar hydrogen contents have been documented in charcoal briquettes from agricultural waste (0.65%–5.71%; Biswas, 2018) and in charcoal from other biomass sources (1.26%–4.11%; Bosire et al., 2023).

Nitrogen content ranged from 1.09% to 1.20%, showing significance differences and the highest value in the potato binder treatment and the lowest in the binder-free control (Figure 4c; Table 4). These results are higher than those reported by Nonsawang et al. (2024) (0.19%–0.79%) and comparable to the 1.56% reported by Mekonen et al. (2024).

Oxygen content varied between 38.73% and 41.87%, with significant differences among treatments (Figure 4d; Table 4). The potato binder treatment had the highest value. These results are within the range of 15.48%–61.94% reported by Nonsawang et al. (2024) and close to the average value of 45.45% reported by Mekonen et al. (2024). Higher oxygen content is advantageous for ignition (Hwangdee et al., 2023).

Sulfur content ranged from 0.03% to 0.04%, with the corn, cassava, and potato binder treatments showing significantly higher values than the control without binder (Figure 5; Table 4). These results fall within the 0.02%–0.08% range reported by Nonsawang et al. (2024) and Patel and

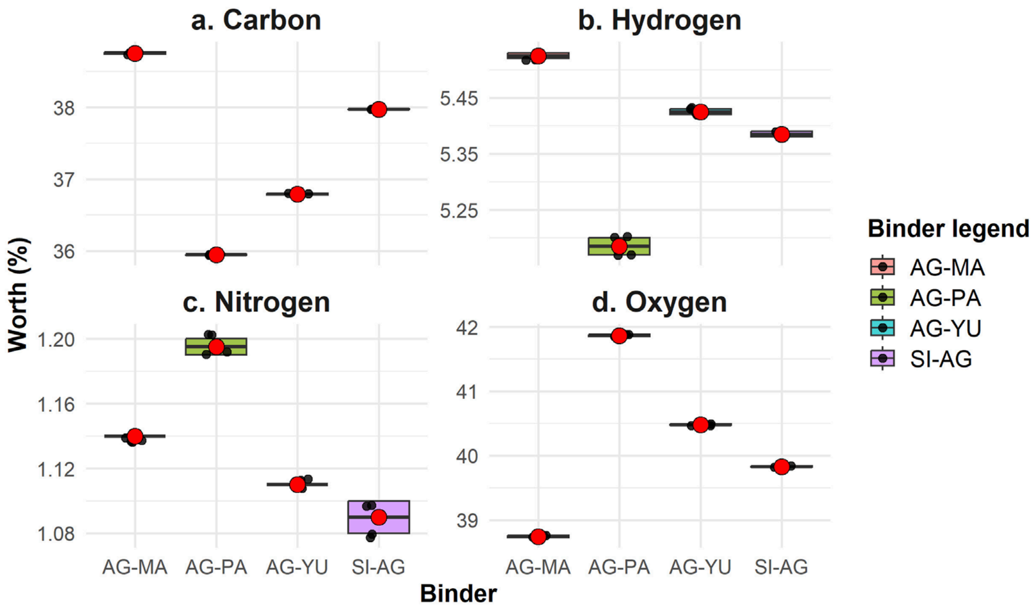

FIGURE 4
Elemental composition of briquettes: **(a)** carbon content and **(b)** hydrogen content. Abbreviations: AG-MA, corn binder; AG-PA, potato binder; AG-YU, cassava binder; and SI-AG without binder.

TABLE 4 Elementary composition and combustion analysis of a briquette made from cacao husk.

Tratamientos		C (%)	H (%)	N (%)	O (%)	S (%)
Without binder	Avg	37.98	5.39	1.09	39.83	0.03
	SD	0.01	0.01	0.01	0.01	0.00
	Group	c	b	a	b	a
Corn starch	Avg	38.76	5.53	1.14	38.75	0.04
	SD	0.02	0.01	0.00	0.02	0.00
	Group	d	d	a	a	a
Cassava starch	Avg	36.79	5.43	1.11	40.48	0.04
	SD	0.01	0.01	0.00	0.01	0.01
	Group	b	c	a	c	a
Potato starch	Avg	35.95	5.19	1.20	41.87	0.04
	SD	0.01	0.02	0.01	0.02	0.00
	Group	a	a	b	d	a

Averages joined by the same letter mean statistically similar averages at 95% confidence intervals according to Duncan's test. Abbreviations: C, carbon; H, hydrogen; N, nitrogen; O, oxygen; S, sulfur.

Gami (2012), and are below the 0.2% threshold considered environmentally safe (Mencarelli et al., 2025). Although sulfur content was negligible, even small amounts should be considered due to their potential impact on emissions.

The highest calorific value (HV) of the binders varied significantly among the different types. The lowest value was recorded for the corn binder treatment, with an average of 3,486.0 kcal kg^{-1}, while the highest was obtained with the cassava binder, averaging 3,617.62 kcal kg^{-1} (Figure 6; Table 2). The results of the present study (3,486.00 and 3,617.62 kcal kg^{-1}) are very similar to those reported by Nonsawang et al. (2024), who obtained values ranging from 3,164.36 to 3,565.88 kcal kg^{-1} in the production of charcoal briquettes from agro-industrial waste using cassava-based industrial binders, indicating that binder selection can influence the final calorific value of briquettes. Palanisamy et al. (2023) reported values between 2,786.74 and 3,737.96 kcal kg^{-1} for briquettes produced with cassava starch as a binder. However, other authors, such as Bonsu et al. (2020), found higher values (4,218.90–4,474.19 kcal kg^{-1}). In many cases, the calorific value of briquettes is influenced not only by the type of binder but also by its concentration, as well as by the feedstock characteristics. For instance, Madhusanka et al. (2025) reported that increasing the proportion of cinnamon sawdust reduced the calorific value.

The mechanical and thermal properties of carbonized composite briquettes are also affected by the amount of biochar, water, and jackfruit-residue binder used (Owino et al., 2024). Most studies on low-pressure briquette development have focused on cassava starch as a binder, highlighting its widespread use and potential (Arewa et al., 2016; Ajimotokan et al., 2019; Aransiola et al., 2019). In this context, Shiferaw et al. (2017) reported an experimental calorific value of 3,824 kcal kg^{-1} for cassava rhizomes, compared with 3,011.40 kcal kg^{-1} for peanut stalks. The carbon content of the studied binders was close to 40%, suggesting that briquettes produced from these feedstocks may have higher calorific values due to their lower capacity for further oxygenation (Anshariah et al., 2020). The lowest

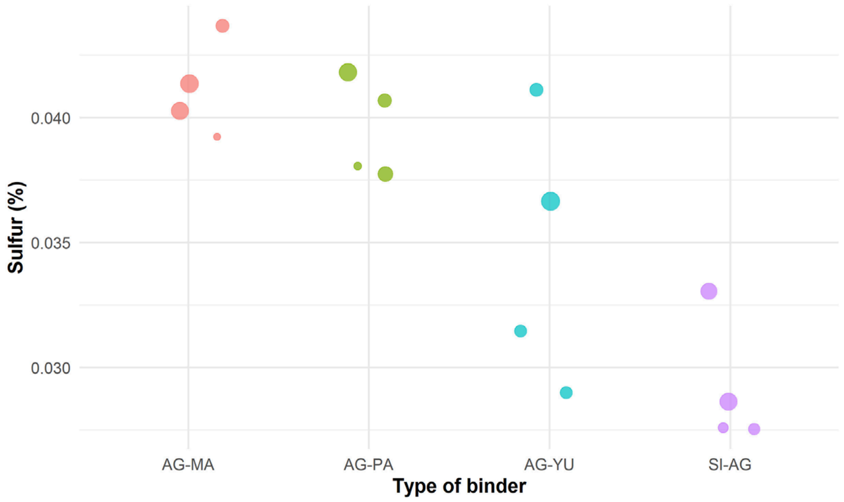

FIGURE 5
Characteristics of sulfur from cocoa pod husk briquettes produced from cassava, corn and potato binders. Abbreviations: AG-MA, corn binder; AG-PA, potato binder; AG-YU, cassava binder; and SI-AG without binder.

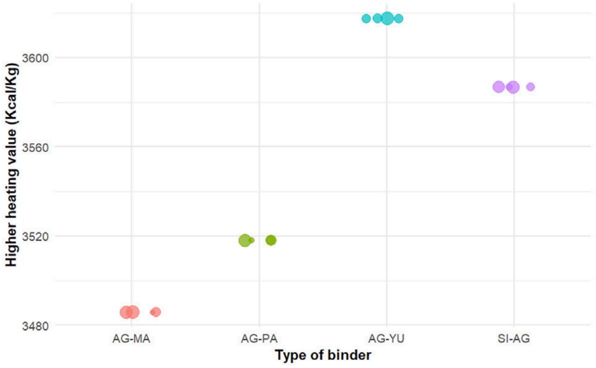

FIGURE 6
Calorific value characteristics of cocoa pod husk briquettes produced from cassava, corn, and potato binders. Abbreviations: AG-MA, corn binder; AG-PA, potato binder; AG-YU, cassava binder; and SI-AG without binder.

HV in this study was found in the corn binder treatment (3,486.0 kcal kg^{-1}), whereas the highest value was observed in cassava binder briquettes (3,617.62 kcal kg^{-1}), in agreement with Ofori and Akoto (2020), who reported 3,998.80 kcal kg^{-1} for carbonized cocoa pod husks. The quality of cassava starch and other extracted plant starches is commonly evaluated through proximate analysis, which includes starch, fiber, fat, ash, and protein contents. However, understanding other physicochemical properties, such as molecular structure and thermal behavior, is crucial to improving their performance (Chamorro et al., 2025). This represents both a limitation of the present study and a recommendation for future research.

Zinla et al. (2021) reported higher HVs in rice husk, rice straw, coffee husk, and cocoa pod husk, with values ranging from 2,925.43 to 3,589.87 kcal kg^{-1}. Notably, cocoa pod husk exhibited the highest HV (3,589.87 kcal kg^{-1}), surpassing that of both rice husk and rice straw. The HV obtained in the present study exceeds that of briquettes produced from both similar and different feedstocks (Zinla et al., 2021; Adjin-Tetteh et al., 2018). Variations in these values may be attributed to differences in the initial moisture content of the raw materials. Adjin-Tetteh et al. (2018) observed that higher feedstock moisture leads to greater energy losses during thermochemical conversion. Consequently, biomass charcoal with lower moisture content tends to exhibit higher calorific values and improved energy conversion efficiency (Akam et al., 2024).

3.4 Final analysis

In Peru, cassava, maize, and potato are staple crops with high nutritional and economic potential. Cassava is a tuber with deep roots, widely accepted in gastronomy, with yields of up to 30 t ha^{-1} and an average market price of approximately USD 0.50 per kilogram. Maize is cultivated throughout the country, reaching yields of up to 10 t ha^{-1}, and is consumed both by the population and as livestock feed, with an average price of USD 0.60 per kilogram. Potato, native to the Peruvian Andes, is a staple food in the national diet, with yields of around 16 t ha^{-1}, remarkable varietal diversity, and multiple culinary uses, and an average price of USD 0.70 per kilogram. Given the low cost and high production of these crops in Peru, their use as binders in briquette production is considered technically and economically viable.

Briquettes produced from cocoa pod husks in this study presented an average organic carbon content of 37.37%, closely matching the values reported by Owino et al. (2024) for rice husk (37.02%) and cocoa pod husk (37.36%). Higher carbon content is associated with improved thermal performance and combustion efficiency (Yunusa et al., 2024). The oxygen content recorded was 40.23%, comparable to values reported by Zinla et al. (2021) for cassava rhizomes (40.7%) and peanut stems (39.1%). In the

TABLE 5 Main studies on the elemental composition in briquette production.

Residues	C (%)	Ce (%)	V (%)	FC (%)	O (%)	H° (%)	HV (kcal/kg)	References
Carbonized sesame stalk	-	9.49	46.80	38.24	-	5.50	4,954.41	Gebrezgabher et al. (2025)
Cow dung	-	15.70	58.40	17.57	-	8.32	4,390.58	
Paper waste	-	10.00	70.30	14.60	-	5.08	3,370.86	
Maize husk	-	-	-	-	-	-	4,670.92	Sekhar and Abdo (2025)
coconut shells	76.79	2.52	23.6	73.86	23.08	-	6,575.05	Nonsawang et al. (2024)
Leucaena leucocephala wood	83.71	2.84	8.82	81.30	15.48	-	6,814.05	
Assorted wood charcoal residues	75.71	10.90	16.00	73.03	19.18	-	6,238.05	
Cassava starch	44.44	0.08	95.60	4.32	61.94	-	3,369.98	
Cassava peel	45.00	7.62	78.40	14.00	52.37	-	3,565.97	
Cassava tubers	41.42	7.28	79.40	13.3	58.73	-	3,164.44	
Cocoa residue		6.5	34.7	58.8		10.5	4,288.00	Akam et al. (2024)
Cassava rhizomes	40	4.6	75.4	16.4	40.7	12.5	3,824.09	Owino et al. (2024)
Groundnuts stalks	42	8.4	75.1	13.1	39.1	12.4	3,011.47	
100% of tobacco stems	-	45.9	-	-	-	8.34	2,343.00	Widjaya et al. (2022)
80% of tobacco stem +20% of coconut shell	-	31.7	-	-	-	7.76	3,782.00	
80% of tobacco stem +20% rice husk	-	36.8	-	-	-	8.62	2,997.00	
Rice husk	37.02	14.96	64.02	13.20	56.26	7.82	3,274.38	Zinla et al. (2021)
Rice straw	33.51	23.70	64.86	1.92	61.00	9.52	2,925.43	
Coffee husk	39.68	8.00	72.94	7.76	51.58	11.30	3,589.87	
Cocoa pod husk	37.36	10.77	66.32	10.61	55.23	12.33	3,441.68	

Abbreviations: C, carbon; Ce, ash; V, volatile; FC, fixed carbon; O, oxygen; H°, moisture and HV, calorific value.

present study, oxygen content in charcoal and binders ranged from 15.48% to 61.94%, with higher concentrations facilitating ignition (Hwangdee et al., 2023). The volatile matter content was 37.16%, similar to the 34.7% reported by Akam et al. (2024) for cocoa residues. Ash content averaged 7.85%, which is consistent with the 6.5% and 4.6% reported by Akam et al. (2024) and Owino et al. (2024) for cocoa residues and cassava roots, respectively. The fixed carbon content was 4.56%, closely aligning with the 4.32% and 7.76% reported by Nonsawang et al. (2024) and Zinla et al. (2021) for cassava starch and coffee husk, respectively.

The average calorific value obtained from cacao pud husk, with four binder traitements was 3,552.06 kcal/kg similar to reported by Nonsawang et al. (2024), Owino et al. (2024), Widjaya et al. (2022), and Zinla et al. (2021) for briquettes made from cassava peels and roots, tobacco, coconut husk, coffee husk, and cocoa pod husk, with corresponding averages of 3,565.97, 3,824.09, 3,782.00, 3,589.87, and 3,441.68 kcal/kg (Table 5). The final analysis of the charcoal confirmed satisfactory performance, demonstrating its suitability and potential for sustainable briquette production.

4 Conclusion

This study demonstrates the technical and environmental feasibility of producing charcoal briquettes from cocoa pod husk using locally sourced starch-based binders, with cassava starch identified as the most efficient option due to its higher calorific value (3,617.62 kcal/kg). The findings indicate that this biofuel not only exceeds the energy performance of briquettes produced with corn or potato binders but also offers notable environmental advantages: low sulfur content (<0.1%), which reduces pollutant emissions, and reduced ash content (7.03%), which enhances combustion efficiency. Corn starch, with the highest fixed carbon content (5.97%), emerged as a promising alternative for applications requiring greater thermal stability. From a practical standpoint, this research provides three main contributions: (i) it validates the use of local agricultural residues (cocoa pod husk and native starches) as feedstock for renewable energy; (ii) it establishes reproducible technical parameters for cocoa-producing communities in the Peruvian Amazon; and (iii) it proposes a scalable circular economy model that delivers environmental benefits by valorizing waste, economic benefits by producing affordable fuels, and social benefits by providing sustainable energy alternatives. To further strengthen these findings, future studies should focus on: (1) optimizing pyrolysis and compaction parameters to enhance energy density; (2) assessing the mechanical durability of briquettes during storage; and (3) evaluating the economic feasibility of medium-scale production. Additionally, to fully elucidate the influence of binders on the calorific value of cocoa pod husk briquettes, comprehensive analyses of physicochemical properties—such as molecular structure, granular morphology, thermal behavior, and starch modifications, particularly in cassava—are essential for improving performance.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

RS: Conceptualization, Data curation, Writing – original draft, Investigation, Methodology, Supervision. AP: Investigation, Writing – review and editing. WN: Data curation, Methodology, Writing – original draft. RS-B: Writing – review and editing, Formal Analysis, Investigation, Validation. GV-T: Conceptualization, Data curation, Writing – original draft, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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