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Experimental study of coconut (*Cocos nucifera*) waste through densification to obtain pellets and briquettes

Estudio experimental de los residuos de coco mediante densificación para obtener pellets y briquetas

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ABSTRACT: In Ecuador, extensive coconut (*Cocos nucifera*) harvesting generates large quantities of waste, including husks, shells, and fibers, posing environmental and economic challenges. This study explores the densification of coconut waste (CW) into pellets and briquettes to address these issues. The process involved raw material collection, pre-treatment, drying, grinding, sieving, mixing, pelletizing, and briquetting, using cassava starch (CS) as a binder. Two CW-to-CS compositions were tested for each type of fuel. Key physical and combustion properties, such as higher heating value, moisture, volatile matter, fixed carbon, ash content, bulk density, and friability, were analyzed. Results showed that the PCA91 pellet sample (90% CW, 10% CS) achieved the best performance with a higher heating value of 15,350 J/g and 11.54% moisture content. Similarly, the BCA91 briquette sample (90% CW, 10% CS) demonstrated better performance with a heating value of 14,950 J/g and 13.75% moisture content. Most samples met the heating value and bulk density requirements of the Swedish SS187120 and Colombian NTC 2060 standards, although some fell short on ash, volatile matter, and fixed carbon content. Adjusting the CW-to-CS ratio could optimize biofuel properties, balancing energy output and stability, highlighting coconut waste's potential as a sustainable biofuel.

Keywords: Coconut waste, Solid biofuels, Pellets, Briquettes, Higher heating value.

Residuos de coco, Biocombustibles sólidos, Pellets, Briquetas, Poder calorífico superior

RESUMEN: En Ecuador, la cosecha intensiva de coco (*Cocos nucifera*) genera grandes cantidades de residuos como cáscaras y fibras, planteando desafíos ambientales y económicos. Este estudio evalúa la densificación de estos residuos (CW) para producir pellets y briquetas como biocombustibles. El proceso incluyó recolección, pretratamiento, secado, molienda, tamizado, mezclado, peletización y briquetización, empleando almidón de yuca (CS) como aglutinante. Se trabajó con dos proporciones CW/CS para cada tipo de combustible. Se analizaron propiedades clave: poder calorífico superior (PCS), humedad, material volátil, carbono fijo, contenido de cenizas, densidad aparente y friabilidad. La muestra de pellet PCA91 (90 % CW, 10 % CS) alcanzó el mejor desempeño con un PCS de 15 350 J/g y 11,54 % de humedad. La briqueta BCA91 (90 % CW, 10 % CS) mostró un PCS de 14 950 J/g y 13,75 % de humedad. La mayoría de las muestras cumplieron los criterios de PCS y densidad establecidos en las normas SS 187120 (Suecia) y NTC 2060 (Colombia), aunque algunas no cumplieron en cuanto a cenizas, material volátil y carbono fijo. Los resultados sugieren que los residuos de coco, con una adecuada proporción de aglutinante, pueden convertirse en biocombustibles sólidos viables. Ajustar la relación CW/CS puede optimizar las propiedades del combustible, equilibrando eficiencia energética y estabilidad, y resaltando el potencial de valorización de estos residuos agroindustriales.

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1. INTRODUCTION

The coconut industry in Ecuador, especially in provinces such as Esmeraldas, Manabí, and El Oro, generates a significant amount of coconut waste (CW) due to massive production, with 1.8 million plants grown on 10,000 hectares producing 360 million coconuts [1]. This process produces approximately 765,000 tons of waste, representing 85% of the gross weight of the coconut. This waste, composed of cellulose, lignin, fiber, and oil, is an environmental concern because of its negative impact on soils and groundwater, as well as encouraging the proliferation of pests and unpleasant odors [2]. However, these wastes also represent an opportunity to produce solid biofuels, such as pellets or briquettes, which could reduce emissions of polluting gases and reduce dependence on fossil fuels, thus contributing to a more sustainable economy and mitigating the negative environmental effects of the coconut industry [3].

CW has turned into a valuable raw material for several industrial applications, especially in the production of solid biofuels such as pellets and briquettes. These residues are composed of 36% cellulose, 12% hemicellulose, and 33% lignin, which gives them a remarkable energy potential [4]. Coconut fiber, together with lignin and cellulose, plays a crucial role in determining the physical and chemical properties required for compaction into pellets and briquettes. Pellets, known for their uniformity, have a higher heating value (HHV) of approximately 4,300 kcal/kg [5]. On the other hand, briquettes, which have a higher HHV of more than 16.9 MJ/kg, a bulk density of 1000 kg/m3, and an ash content of less than 0.7%, offer an efficient and sustainable alternative to fossil fuels [6]. The selection of binders and their composition is essential to maximize the performance and energy efficiency of these biofuels derived from coconut residues, thus providing a sustainable and effective solution for the utilization of these by-products.

Since the 20th century, biofuels derived from CW have been investigated as sustainable alternatives to fossil fuels. In Ecuador, although the adoption of these biofuels has been limited due to an economy focused on fossil fuels, there is a growing need for alternatives that protect the environment [7]. CW biomass, which includes husks, fibers, and pulp, varies in quantity depending on coconut variety, climate, and agricultural practices. These wastes are useful not only for energy generation but also for compost production. Several studies have shown that residual biomass can be converted into high-quality briquettes and pellets through appropriate compaction processes, which contributes to reducing deforestation and improving energy efficiency [8].

The production of pellets and briquettes from CW and other materials has shown promising results. Pellets, characterized by their uniformity and quality, have a HHV close to 4,300 kcal/kg, while briquettes, with a higher high heat value of more than 16.9 MJ/kg and a bulk density of 1000 kg/m3, present an efficient and sustainable alternative to fossil fuels [9]. Proper binder selection is crucial to maximizing the performance and energy efficiency of these biofuels. Recent studies have explored various combinations of materials and binders to improve the quality of briquettes and pellets, highlighting the importance of continued research in this field to optimize densification processes and increase the viability of solid biofuels as a sustainable energy solution [10].

The densification of solid biofuels, such as pellets and briquettes, has advanced thanks to the evolution of various biomass processing and compaction techniques. This process, whose basic principles date back to ancient times with the use of hydraulic and mechanical presses, gained greater importance during the energy crisis of the 1970s, when research intensified in search of alternatives to fossil fuels [11]. Over the years, numerous patents have documented technological advances in pressing technology, improving both energy efficiency and the quality of the final product. Thus, the densification of solid biofuels has been consolidated as a response to the need for more sustainable and manageable energy sources [12].

The origin of pellets as an energy source dates to the United States after the economic crisis of 1929. In Idaho, a pine sawmill reused sawdust and pruning waste to create "presto logs," large blocks of compressed sawdust that later evolved into small, more manageable cylinders [13]. Although their global recognition as a renewable and sustainable energy source was consolidated a decade ago, pellets have improved in production efficiency and have diversified in their use, including electricity generation and as a raw material in various industries.

Biomass briquettes, with their cylindrical or brick shape, began to be manufactured in the 19th century from biodegradable materials such as pulverized charcoal and starch as a binder [14]. This renewable and environmentally friendly product has gained popularity due to its ability to replace firewood, offering additional advantages such as more efficient and controlled combustion. From the patenting of the first industrial process for briquetting in 1865 in the United States to its global expansion, briquettes have been used in applications such as residential heating, industrial processes, and power generation [15].

The role of the binder in biomass densification is fundamental. A binder is a substance that holds material particles together. Since ancient times, drying oils have been used as binders in painting and construction, documented in recipe books and treatises on artistic technology [16]. Over time, the variety and complexity of these additives have improved the characteristics of the final product. In biomass pelleting and briquetting, the proper choice of binders is crucial to maximize the yield and energy efficiency of solid biofuels [17].

Biomass pelleting and briquetting are essential technologies for converting agricultural, forestry, and industrial waste into high-quality solid biofuels. These processes allow us to overcome the limitations of the low bulk density of lignocellulosic biomass, offering more uniform properties and higher energy density. Continuous research in the selection of optimal binders and compaction techniques is essential to improve the quality and efficiency of these biofuels, thus contributing to a sustainable and environmentally friendly energy solution [12].

The purpose of this work is to take advantage of CW, through densification, to obtain solid biofuels. To conduct this process, it is required to collect the CW and conduct a pretreatment for its use as raw material for the production of pellets and briquettes.

In addition, the combustion characteristics of CW will be obtained, and the compositions of biomass and binder material will be determined for the production of pellets and briquettes. Finally, an exhaustive analysis of the characteristics of the pellets and briquettes produced will be performed to verify the suitability of this biomass to produce solid biofuels.

2. MATERIALS AND METHODS

This research focuses on an experimental and exploratory approach, with the objective of producing pellets and briquettes from CW. Taking into account the Swedish standard for biofuels and peat SS187120 [18] and the Colombian technical standard NTC 2060 [19], detailed analyses were conducted before and after the production of pellets and briquettes to evaluate the efficiency of the conversion of CW into solid biofuels.

Following a previous investigation to establish a solid methodology to produce biofuels from biomass waste [20], cassava starch (CS) (*Manihot esculenta*) was chosen as the binder material to improve the structural integrity of the pellets, making them more durable and resistant to breaking or crumbling during handling, transportation, and storage.

Data on ash content, moisture content, fixed carbon, volatile matter content, and HHV of the CW pellets and briquettes was collected and analyzed [21]. The experimental design includes stages from sample collection and preparation to the production of pellets and briquettes through pelleting and briquetting processes. Thus consolidating a comprehensive and efficient approach in the transformation of CW into a sustainable energy source [22].

2.1. Pellets and briquettes production process

This process began with the collection of CW from several commercial establishments where coconuts are sold in the south of the city of Guayaquil, Ecuador. Then, the endocarp of the coconut was removed, leaving the mesocarp (fibrous husk) and exocarp (outer layer) of the coconut for use as solid biofuel. Following a previous investigation [23], a size reduction was conducted for better handling of the waste obtained. The CW biomass was analyzed to obtain results on the parameters such as ash content, volatile matter, moisture content, fixed carbon, and HHV. An amount of 200 grams of CW was required to conduct the analyses. Then, the rest of the waste was sun-dried for 5 days, followed by a drying stage in an oven at 73 °C for 10 hours, following a previous work [24]. Then, grinding and sieving were conducted to obtain particle sizes of 0.5–1 mm for pellets and 3–8 mm for briquettes.

For pellet and briquette production, a prior mixing was performed. Two CW-to-CS compositions were used: 90% CW – 10% CS, named as PCA91 and BCA91 for pellets and briquettes, respectively, and 70% CW – 30% CS, named as PCA73 and BCA73 for pellets and briquettes, respectively. For the pellet production, a screw mechanical press was used with a matrix with a diameter of 10 mm and a height of 40 mm to produce pellets of 10 mm in diameter and a length of 15 mm, complying with the dimensional requirements established in the standards, following a previous work [25]. For briquettes, a mechanical press was used, with a mold with a diameter of 5 cm and a height of 10 cm. The final dimensions of the briquettes were 5 cm in diameter and 6 cm in length, following the methodology reported in [26].

The use of cassava starch as a binder was chosen not only due to its local availability and low cost, but also because of its biodegradability and proven binding efficiency in previous biomass densification studies. Its high starch content contributes to cohesive and durable pellet and briquette structures, making it a suitable natural additive in solid biofuel formulations.

2.2. Samples physical and combustion characteristics

2.2.1. Higher heating value

In this stage, the determination of the HHV was conducted for pellets and briquettes, based on the ASTM D240 standard [27].

2.2.2. Moisture content

A moisture content determination test was conducted following the ASTM C25 standard [28], using Equation 1.

$$Moisture\ content = \frac{B}{A} \cdot 100 \quad (1)$$

where:

A: Initial mass (g).

B: Final mass (g).

2.2.3. Ash content

To determine the ash content, the INEN 520 standard [29] was followed, which consists of placing the sample in a muffle furnace and heating it to a temperature between 500 and 700 °C and then weighing it after cooling. In this study, the temperature was fixed at 600 °C for all samples to ensure consistency in the results. Equation 2 was used.

$$Ash\ content = \frac{m_3 - m_1}{(100 - H) \cdot m_2 - m_1} \cdot 100 \qquad (2)$$

where:

m_1: Mass of the empty crucible (g).

m_2: Mass of the empty crucible with the sample (g).

m_3: Mass of the crucible with the ashes (g).

H: Moisture content in the sample (%).

2.2.4. Volatile matter content

This test is based on the ASTM D-3175 standard [30], which determines the percentage value of a sample through calcination at 950°C and subsequent weighing. Equation 3 was used.

$$VC = \left(\frac{m_2 - m_3}{m_2 - m_1} \cdot 100\right) - H \qquad (3)$$

where:

VC: Volatile matter content (%).

m_1: Mass of the empty crucible and the lid (g).

m_2: Mass of the empty crucible and the lid plus 1g of sample (g).

m_3: Mass of the empty crucible and lid plus the heated sample from the muffle furnace (g).

H: Moisture content (%).

2.2.4. Fixed Carbon content

To determine the fixed carbon content, the ASTM-D3172 standard [31] was followed, which is determined by calculations using Equation 4.

$$CC = 100 - (H + C + MV) \qquad (4)$$

where:

CC: Fixed Carbon content (%).

K: Moisture content (%).

C: Ash content (%).

MV: Volatile matter content (%).

2.2.5. Bulk density

The procedure followed to determine the bulk density of pellets and briquettes was conducted by calculating their volume and mass, and then using Equation 5:

$$\rho = \frac{m}{v} \qquad (5)$$

where:

ρ: Bulk density (kg/m^3).

m: Mass (kg).

v: Volume (m^3)

2.2.6. Friability index

This test consisted of dropping a determined amount of samples of pellets and briquettes from a height of 1 meter from the ground onto a surface [33]. Then, the elements into which the samples were fragmented were counted. Then the friability index was determined using Equation 6.

$$Fr = \frac{Ei}{Ef} \qquad (6)$$

where:

Fr: Friability index.

E_i: Initial elements.

E_f: Final elements.

2.2.7. Mass loss analysis for CW pellets and briquettes

Following a previous investigation for this analysis [34], two pellets and two briquettes of each configuration were chosen and placed separately in a muffle furnace at a temperature of 350ºC. The pellets and briquettes were removed from the muffle furnace every 30 seconds to measure mass loss over time. This process was repeated until no noticeable changes were observed in the mass of the pellets and briquettes over time.

3. RESULTS AND DISCUSSION

3.1. Combustion characteristics analysis of CW

Table 1 shows the results of the CW combustion characteristics prior to the production of pellets and briquettes (Figure 1). It is possible to see a moderate HHV of 12,858.33 J/g, lower than typical biomass fuels like wood (usually >15,000 J/g) [9], but within a usable range for low to medium energy applications. The CW's HHV is influenced by a notably high moisture content of 19.68%, this can negatively impact combustion efficiency by requiring more energy to evaporate water before actual combustion begins. Since high moisture reduces the HHV, a drying stage was carried out at 70 °C for 72 hours. At 5.74%, CW has a relatively high ash content compared to wood-based fuels, which typically range from 0.5% to 2% [9]. This parameter suggests that CW may produce significant ash waste, which would need to be managed, particularly in larger-scale applications. CW shows a 72.26% of volatile matter, which can contribute to easy ignition and fast combustion. With only 2.32% fixed carbon, CW has low structural carbon content, meaning it contributes minimally to sustained combustion [35]. For efficient biofuel applications, a higher fixed carbon content is preferable, as it sustains heat release over a longer period. The low fixed carbon suggests that CW alone might not be ideal for applications requiring long-lasting combustion, and mixing with higher fixed-carbon materials may improve performance. Another study reported a higher HHV of 15,900 J/g, with a lower moisture content of 10.10%, 5.65% ash content, 65.50% volatile matter, and 18.75% fixed carbon for CW [36]. The differences in HHV are attributed to the variation in moisture content, and although the ash content is similar, the differences in fixed carbon highlight the impact on the volatilization of the fuel [36].

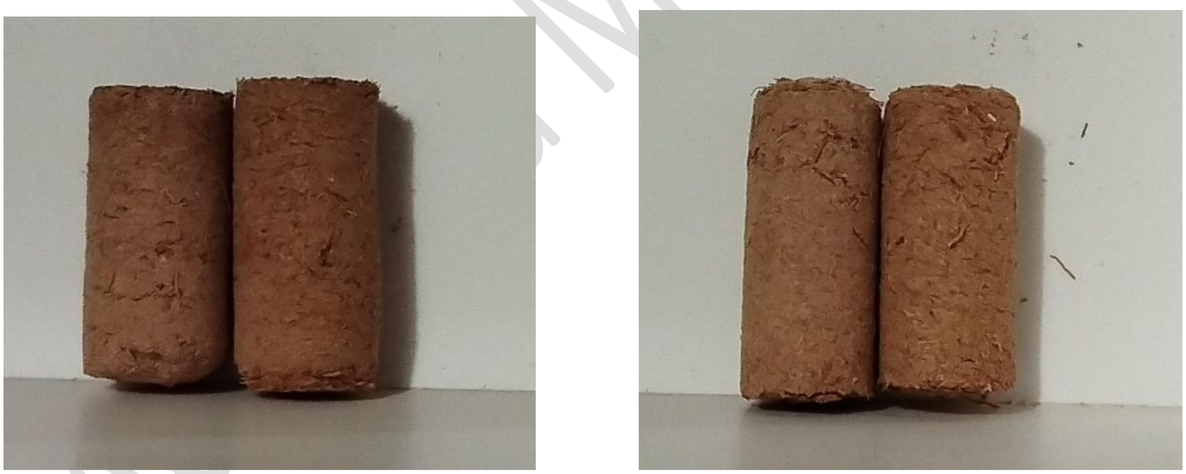
Table 1 Results of CW combustion characteristics

Parameter	**Value**	**Test method**
HHV (J/g)	12,858.33	ASTM D240
Moisture content (%)	19.68	ASTM C25
Ash content (%)	5.74	INEN 520
Volatile matter (%)	72.26	ASTM D3175
Fixed carbon (%)	2.32	ASTM D3172

Figure 1 Sun-dried CW biomass

3.2. CW pellets analysis

Figure 2 shows two pellet sample configurations: Figure 2a shows a PCA91 sample (90% CW – 10% CS); Figure 2b shows a PCA73 sample (70% CW – 30% CS). Table 2 shows the results of the parameters evaluated for the two pellet compositions. The parameters of HHV, moisture content, and ash content were compared with the Swedish standard 187120 [18], while the rest of the parameters were compared with a previous investigation [37].



(a) (b)

Figure 2 a) PCA91 pellets. b) PCA73 pellets

Table 2 Results of bulk density, friability and combustion characteristics of CW pellets

Parameter	**Sample**		**Test method**	**Reference value**
	PCA91	**PCA73**		
HHV (J/g)	15,350.00	15,150.00	ASTM D240	>15100.00 [18]

Moisture content (%)	11.54	12.26	ASTM C25	<12 [18]
Bulk density (kg/m^3)	830	1150	Mass-to-volume	>500 [18]
Ash content (%)	4.94	4.56	INEN 520	<1.5 [18]
Volatile matter (%)	76.07	76.53	ASTM D3175	66.05 [37]
Fixed carbon (%)	7.45	6.65	ASTM D3172	25.52 [37]
Friability index	0.9	0.6	ASTM D440	0.975 [18]

In terms of HHV, both PCA91 and PCA73 exhibit values close to the reference standard of 15,100 J/g [18]. Specifically, PCA91 demonstrates a slightly higher HHV (15,350 J/g) than PCA73 (15,150 J/g), indicating marginally better energy output. This result suggests that increasing the CW content in the pellet composition slightly enhances energy value as indicated in [38], aligning PCA91 more closely with the standard. Therefore, both compositions are viable as biofuels, with PCA91 being the more efficient option. Concerning the moisture content in both samples —11.54% for PCA91 and 12.26% for PCA73— falls within or slightly above the <12% threshold in SS 187120. Although PCA91 is closer to the standard limit, PCA73's higher moisture content may slightly hinder combustion efficiency. In practical terms, PCA91 would likely ignite more easily and burn consistently, while PCA73 may require additional drying for optimal performance. Bulk density, a critical factor for storage and transport efficiency, varies significantly between the samples: PCA91 has a bulk density of 830 kg/m^3, while PCA73 has 1150 kg/m^3. Both values exceed the minimum requirement of 500 kg/m^3, which is favorable for compact storage [39]. The higher bulk density of PCA73 could offer logistical advantages, although this comes with a trade-off in terms of its slightly lower HHV and increased moisture content. PCA73's density may appeal to applications where space efficiency is a priority, despite its marginally lower fuel efficiency. Ash content in both samples is notably higher than the standard limit of <1.5% [18], with PCA91 at 4.94% and PCA73 at 4.56%. High ash content can reduce combustion efficiency, create residue build-up, and increase maintenance requirements. However, the value of ash content of 4.47% reported in [37] is very similar compared with the ash content obtained for PCA91 and PCA93 pellets. This characteristic could limit the suitability of these pellets for applications where minimal ash production is required. Both samples show high volatile matter content (76.07% for PCA91 and 76.53% for PCA73), exceeding the reference value of 66.05% reported by [18]. High volatile matter can improve ignition but may also result in a faster burn rate, requiring careful management in combustion systems to maintain consistent heat output. Conversely, fixed carbon content is low—7.45% for PCA91 and 6.65% for PCA73—against the reference of 25.52% [37], indicating that the pellets may not sustain long-lasting combustion. It is important to mention that the pellet composition reviewed in [37] was 10% corn spathes, 30% Movingui sawdust, and 60% coconut shells. Together, these characteristics suggest that these CW-based pellets would perform best in applications requiring quick ignition and short, intense heat release rather than prolonged burning. The results of the friability index were obtained with an average of 5 repetitions for each sample. The friability index shows that PCA91 and PCA73 had values of 0.9 and 0.6, respectively, both of which are below the reference standard of 0.975 [18]. This difference could be attributed to the binder content, where a higher amount of coconut biomass in PCA91 samples provides better bonding due to fiber interlocking, indicating good mechanical durability [40].

3.3. CW briquettes analysis

Figure 3 shows two configurations of briquettes: BCA91 contains 90% CW and 10% CS (Fig. 3a) and BCA73, which contains 70% CW and 30% CS (Fig. 3b). Table 3 shows the results of the parameters evaluated for the briquette samples. HHV, moisture, and ash content were compared with the Colombian Technical Standard NTC 2060 [19], while the rest of the parameters were compared with a previous investigation [42].

(a) (b)

Figure 3 a) BCA91 briquette. b) BCA73 briquette

Table 3 Results of bulk density, friability and combustion characteristics of CW briquettes

Parameter	**Sample**		**Test method**	**Reference value**
	BCA91	**BCA73**		
HHV (J/g)	14,750.00	13,550.00	ASTM D240	>12500.00 [19]
Moisture content (%)	13.75	17.35	ASTM C25	<12 [19]
Bulk density (kg/m^3)	760	790	Mass-to-volume	>500 [19]
Ash content (%)	4.14	4.35	INEN 520	<1,5 [19]
Volatile matter (%)	78.19	76.96	ASTM D3175	67 [42]
Fixed carbon (%)	3,92	1,34	ASTM D3172	15,6 [42]
Friability index	0.8	0.7	ASTM D440	0.975 [18]

The HHV of both briquettes exceeds the NTC 2060 standard requirement of 12,500 J/g [19], with BCA91 at 14,750 J/g and BCA73 at 13,550 J/g. BCA91 shows a notably higher HHV, suggesting that the greater proportion of CW enhances energy content, making it more efficient for fuel applications. This difference implies that BCA91 could be preferred for energy-demanding applications, while BCA73, with its lower HHV, might be suited for less intensive uses. In terms of moisture content, both samples exceed the NTC 2060 limit of 12%, with BCA91 at 13.75% and BCA73 significantly higher at 17.35%. The elevated moisture content, particularly in BCA73, could reduce combustion efficiency and hinder ignition. For practical applications, both briquettes would benefit from further drying processes to improve their compliance with the moisture standard, which would, in turn, enhance energy efficiency and reduce the risk of incomplete combustion. Regarding bulk density, both BCA91 and BCA73 exceed the minimum bulk density requirement of 500 kg/m³ specified in the NTC 2060, with BCA91 at 760 kg/m³ and BCA73 at 790 kg/m³. These values indicate that both briquettes are relatively compact and well-suited for storage and transportation. The slightly higher density of BCA73 could favor transport efficiency, though this advantage may be offset by its higher moisture and lower HHV. The ash content for both samples (4.14% for BCA91 and 4.35% for BCA73) is notably above the NTC 2060 standard of <1.5%, this might be due to the natural composition of CW as indicated in [41], which could present issues for combustion efficiency and maintenance. High ash content leads to increased residue post-combustion. This characteristic makes both briquettes less suitable for applications requiring low maintenance and minimal residue, suggesting they may need ash-reducing additives or preprocessing adjustments. The volatile matter content in both briquettes is high (78.19% for BCA91 and 76.96% for BCA73), exceeding the 67% reported in [42]. This might be attributed to the compositions used in the production of the briquettes; a higher starch content has a slightly lower volatile matter due to the presence of more non-volatile components in the starch compared to coconut waste, as reported in [43]. While high volatile matter can enhance ignition, it may also result in a quicker burn rate, which could be less desirable for applications requiring sustained heat. On the other hand, the fixed carbon content is low —3.92% for BCA91 and 1.34% for BCA73— compared to the reference value of 15.6% [42]. Low fixed carbon suggests limited long-term burning potential, meaning these briquettes may be better suited to applications requiring rapid ignition and short bursts of heat rather than prolonged combustion [44]. Regarding friability, BCA91 sample had a friability index of 0.8, while sample BCA73 achieved a value of 0.7. CW can provide more robust and friction-resistant characteristics when it is not saturated with binder. In BCA73, the percentage of binder selected may result in a more homogeneous structure but less resistant to shock and friction [45].

3.4. Effect of the composition on the mass loss for CW pellets

Figure 4 displays the mass loss over time for PCA91 and PCA73 pellet samples at a temperature of 350 ºC. Mass loss was monitored to evaluate the pellets' thermal stability and resistance to decomposition over time, which is critical for biofuel applications. An analysis of the trends observed and the implications of the results is presented below:

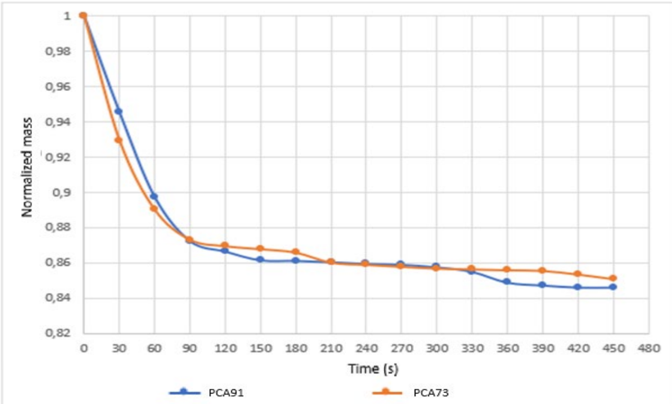


Figure 4 Normalized mass vs time for pellets samples

3.4.1 Initial Mass Loss

Both compositions show a rapid initial mass loss within the first 60 seconds. This phase likely corresponds to the evaporation of moisture content and the release of volatile compounds. The rapid decrease in normalized mass at the beginning is typical in biomass materials, where moisture and volatiles are released quickly at the start of heating. PCA73 shows a slightly slower rate of initial mass loss compared to PCA91, which may be due to the different proportions of CW, impacting the initial moisture and volatile release rates.

3.4.2 Stabilization Phase

After the initial steep decline, both compositions enter a more stable phase around 150–180 seconds, where the mass loss rate decreases significantly. However, PCA73 stabilizes at a slightly higher normalized mass (~0.86) compared to PCA91 (~0.84). This difference suggests that PCA73 retains more mass during combustion, possibly due to its lower CW content or higher fixed carbon structure, which can enhance stability and reduce mass loss under prolonged heating conditions.

3.4.3 Comparative Stability

By the end of the test (at 450 seconds), PCA73 consistently retains a marginally higher normalized mass than PCA91. This result could imply that the lower CW composition in PCA73 provides increased thermal stability, possibly due to the interaction between the CS binder and the CW. The binder might contribute to a more resilient structure, reducing thermal degradation compared to the higher CW concentration in PCA91.

3.4.4 Implications for Fuel Performance

The slightly higher stability of PCA73 might make it more suitable for applications requiring sustained combustion with minimal mass loss over time. However, PCA91, with its higher CW concentration, may offer higher energy content but at the cost of increased initial volatility and mass loss. These characteristics should be considered depending on the intended use of the pellets. PCA91 could be ideal for applications needing a quick energy release, while PCA73 may be more appropriate where slower, prolonged burning is desired.

3.4.5 Role of Composition

The different behavior between PCA91 and PCA73 highlights the significant role of CW composition in determining the thermal properties of the pellets. The increased cassava starch content in PCA73 contributes to a structure that is less prone to rapid degradation, potentially offering improved durability and resistance to thermal breakdown.

3.5. Effect of the composition on the mass loss for CW briquettes

Figure 5 shows the mass loss behavior over time for BCA91 and BCA73 briquette samples at a temperature of 350ºC. In the same way as it was done for the pellets, a detailed analysis is presented below:

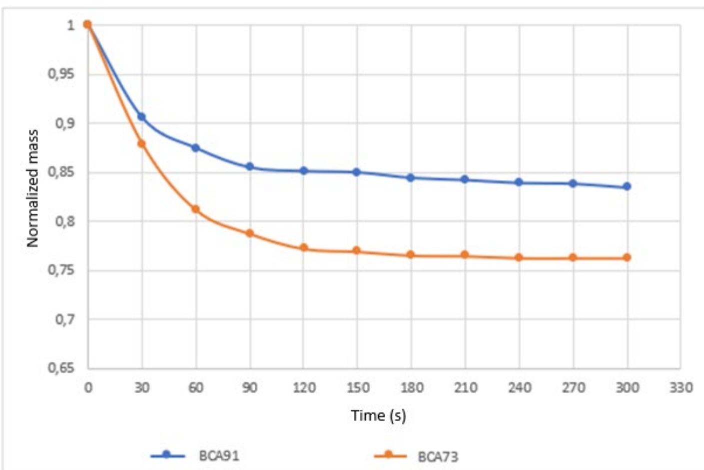


Figure 5 Normalized mass vs time for briquettes samples

3.5.1 Initial Mass Loss

Both briquette types exhibit a rapid initial mass loss in the first 60 seconds, which is typical in biomass combustion as moisture and volatiles are released. However, the rate of mass loss differs between the two. BCA73 shows a steeper decline, stabilizing at a lower normalized mass around 0.77, compared to BCA91, which stabilizes near 0.87. This indicates that BCA73, with a higher CS content, experiences greater decomposition initially, likely due to its composition having a lower fixed carbon content and higher moisture or volatile matter as shown previously in Table 3.

3.5.2 Stabilization Phase

After the initial rapid mass loss, both samples transition into a stabilization phase, where the rate of mass loss slows significantly. During this period, BCA91 retains more of its mass than

BCA73, which suggests that it has greater thermal stability. The higher CW content in BCA91 seems to contribute to this stability, as CW likely provides a more carbon-rich structure that resists further mass loss at this stage.

3.5.3 Comparative Stability

Comparing the two samples, BCA91 demonstrates superior stability with higher retained mass throughout the combustion period. The enhanced stability of BCA91 could be attributed to its higher proportion of CW, which likely contains more fixed carbon that resists decomposition. In contrast, BCA73's lower CW content and higher starch percentage appear to reduce its stability under prolonged heating.

3.5.4 Implications for Fuel Performance

The results have important implications for the fuel performance of each briquette type. BCA91, with its slower and more stable mass loss, may be better suited for applications requiring sustained combustion and a consistent heat release over time. In contrast, the faster mass loss observed in BCA73 could be advantageous in scenarios that require rapid energy release and easier ignition, although it may not burn as steadily or for as long.

3.5.5 Role of Composition

The CW-to-CS ratio plays a critical role in the briquettes' combustion characteristics. The higher CW content in BCA91 enhances its thermal stability and makes it better suited for long-duration burning. The higher cassava starch content in BCA73, while potentially aiding in the binding of the material, appears to lead to quicker decomposition and less thermal resilience. This suggests that adjusting the CW-to-CS ratio allows for customization of the fuel properties to meet different energy demands.

These findings are also consistent with research conducted in the region on the valorization and pelletization of lignocellulosic materials. For example, in Colombia, Orrego-Romero et al. [46] analyzed the effects of binder addition to activated carbon powders to form structured pellets as catalyst supports. They concluded that under optimized pyrolysis conditions, pelletized catalysts retained high surface area and structural integrity, validating the relevance of pellet formation techniques for applications beyond combustion. Similarly, Gallo-Corredor and Sarria-Villa [47] emphasized the importance of developing technologies for the rational use of lignocellulosic waste in the Cauca region, highlighting its potential for producing briquettes and other value-added products with environmental and socio-economic benefits.

4. CONCLUSION

The combustion characteristics of pellets and briquettes from CW have been experimentally investigated. The results obtained indicate that the PCA91 pellet sample (90% coconut waste, 10% cassava starch) showed the best performance with a HHV of 15350 J/g and a moisture content of 11.54%, making it better than PCA73 for energy efficiency and potentially more suitable for transport and storage. Concerning briquettes, the BCA91 sample (90% coconut waste, 10% cassava starch) showed the best performance with a HHV of 14950 J/g and a moisture content of 13.75% compared with BCA73, but high ash content and low fixed carbon are drawbacks for sustained heating applications. It could be improved by further drying and ash-reduction processes. All of the pellets and briquette samples complied with the values of HHV, and bulk density established in the Swedish and Colombian biofuel standards SS187120 and NTC 2060, respectively. Some parameters, such as ash content, volatile matter, and fixed carbon, turned out to be out of the standards. Regarding the effect of the composition on the mass loss, both compositions for pellets and briquettes have distinct advantages. PCA91's higher CW content provides more rapid energy release, while PCA73 offers greater thermal stability and lower mass loss over time, potentially enhancing its suitability for continuous heating applications. BCA91 retains more mass over time and is more stable, making it ideal for applications needing sustained burning and heat, BCA73 loses mass more quickly, which could be useful for applications requiring rapid combustion and higher initial energy release. Adjusting the CW-to-CS ratio could be a strategic approach to tailor pellet and briquette properties for specific biofuel requirements, balancing energy output with stability. This study offers important insights into densified coconut waste, showing an interesting potential as an alternative fuel for combustion systems.

5. Declaration of competing interests

We declare that we have no significant competitive interests, such as financial, professional, or personal interests that interfere with the complete and objective presentation of the work in this document.

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7. Author contributions

L. Velázquez-Araque: Conceived and designed the study, performed data analysis and reviewed and edited the manuscript. J. Teneta-Ibarra and F. Sáenz-Gómez: Collected the data, performed the methodology of the investigation, and wrote the original draft.

8. Data availability statement

The data that support the findings of this study are openly available in Mendeley Data at https://data.mendeley.com/datasets/xxnmbpgrgd/1

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