

Article

Characterization of Briquettes from Potato Stalk Residues for Sustainable Solid Biofuel Production

Marlon Andrés Piarpuezán Enríquez ¹, Daniel Roberto Zapata Hidalgo ^{2,*} and Fernando Pantoja-Suárez ¹

¹ Departamento de Materiales, Facultad de Ingeniería Mecánica, Escuela Politécnica Nacional, Ladrón de Guevara E11-253, Quito, Ecuador; marlon.piarpuezan@epn.edu.ec (M.A.P.E.); fernando.pantoja@epn.edu.ec (F.P.-S.)

² Departamento de Ciencias de la Energía y Mecánica, Universidad de las Fuerzas Armadas ESPE, P.O. Box 171-5-231B, Sangolquí, Ecuador

* Correspondence: drzapata@espe.edu.ec

Abstract: The development of biofuels aligned with the circular economy has gained increasing attention as a sustainable alternative to non-renewable energy sources. This study aims to evaluate the physical and thermal properties of biomass briquettes derived from potato stalk residues to assess their potential as biofuels. For this, dried potato stalk residues were subjected to pyrolysis for carbonization, followed by grinding and mixing with potato and achira binders in proportions of 10% and 20%, respectively. The briquetting process was performed at a pressure of 10 MPa with compaction times of 30 and 60 s. Scanning electron microscopy (SEM) revealed a porous structure with uniform binder distribution, while Raman spectroscopy confirmed the presence of D and G bands, indicative of amorphous carbon structures with graphite-like imperfections. Thermogravimetric analysis (TGA) determined a moisture content of 10%, which ensures stability. Non-carbonized briquettes exhibited higher compressive strength, withstanding forces in excess of 400 N at 20% deformation. The average calorific value of both briquette types was 15 MJ/kg, comparable to biofuels derived from sugarcane bagasse and rice hulls, with samples exceeding the 12 MJ/kg threshold for biomass fuel classification. These results indicate that potato stalk briquettes could be a viable biofuel alternative to support renewable energy diversification.

Keywords: biomass preparation process; pyrolysis; solid biofuel; potato stalk residues



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1. Introduction

The growing global demand for energy poses significant challenges in the transition from conventional fossil fuels to sustainable, low-carbon energy sources. As energy consumption increases, it is imperative that emerging renewable alternatives not only replace fossil fuels but also adapt to the growing demand [1]. In many tropical countries, charcoal production is highly dependent on natural forests, raising significant environmental concerns due to unsustainable logging practices and lack of effective forest management policies [2]. In addition, substantial waste generation in the agricultural, forest, textile, and food sectors aggravates environmental degradation and contributes to climate change [3]. A viable alternative to address these challenges is the production of biomass briquettes. These briquettes use agricultural residues, which reduces waste accumulation and, at the same time, provides a carbon-neutral energy source that emits less harmful gases than conventional fuels [4]. Furthermore, biomass briquettes support economic opportunities by fostering the development of technologies that convert waste biomass into efficient solid fuels, thus reducing deforestation and improving living conditions [5]. In developing

countries, approximately 75% of the population relies on biomass for cooking, contributing 14% to the total global energy consumption [6]. Due to their favorable chemical, physical, and calorific properties, biomass-based fuels serve as a viable alternative to conventional charcoal, especially when derived from a wide range of lignocellulosic residues such as agricultural waste, animal manure, and forest biomass [7].

Numerous studies have explored the viability of producing briquettes from lignocellulosic biomass as an alternative to charcoal derived from primary forests. Lignocellulosic biomass consists mainly of lignin, cellulose, and hemicellulose, along with organic components such as lipids, which enhance its energy properties [8,9]. Cellulose contributes to high calorific value and efficient combustion, while hemicellulose and lignin play crucial roles in biomass densification. Hemicellulose provides adhesive properties that improve the cohesion of the briquette, while lignin improves mechanical strength at elevated temperatures, resulting in a more durable product with optimized combustion efficiency [10–12]. To fully exploit the energy potential of lignocellulosic biomass, a thermochemical processing technique must be applied. Pyrolysis is a particularly favored method for converting agricultural residues into high-quality briquettes because it is the process of breaking down complex organic molecules into simpler and more energy-dense compounds. In particular, biochar production is obtained from the repolymerization of aromatic hydrocarbons with the formation of charcoal and volatiles, resulting in a higher carbon content and thermal stability during the repolymerization process [13]. Pyrolytic treatment thermochemically transforms agricultural waste and significantly improves their energy properties; for example, palm husk and corncob briquettes are capable of producing energy due to their high calorific values [14,15]. This process also reduces the moisture content of the biomass as well as the amount of volatile matter, both of which are essential for improved combustion efficiency and storage stability [15,16]. It is important to consider that temperature and pressure have an impact on the yield and quality of pyrolysis products, namely that a generally higher process temperature improves biochar formation and, simultaneously, decreases its yield, which depends on the feedstock and operational parameters [17]. Furthermore, the application of pyrolysis enhances environmental sustainability by offering an effective solution for the management of agricultural residues. This process not only reduces the volume of waste, but also reduces net CO₂ emissions during biomass combustion, as part of the carbon released is reabsorbed by plants through the natural carbon cycle [18–20].

The additional income from agricultural residues makes this an economically viable option for farmers [19]. However, optimizing the technology for specific biomass feedstocks and industrial scale-up remain active areas of challenge, along with improving efficiency and cost competitiveness, especially for the agricultural waste-rich regions of the developing world. In addition, evaluating unintended consequences ensures that addressing concerns about the environmental impact of large-scale adoption on the sustainable longevity of pyrolysis-based briquette production remains critical.

This study aims to evaluate the potential of potato stalk residues from the northern highlands of Ecuador as raw material for carbonized (pyrolyzed at 350 °C) and non-carbonized briquettes. Specific objectives include the following: (i) producing briquettes with varying binder types, binder weight fractions, and compaction times; (ii) describing the production process and characterizing the thermal and mechanical properties; and (iii) comparing their calorific values with those of common solid biofuels. By achieving these objectives, this study contributes to the existing knowledge on solid biofuels and provides a foundation for future research on the use of agricultural residues for sustainable energy production.

2. Materials and Methods

2.1. Biomass Preparation

The cultivation of potato (i.e., *Solanum tuberosum*) occupies an important role within the agricultural framework of Ecuador, being recognized as the third most produced crop in the nation in recent years, with a vast area of 19,390 hectares [21]. However, currently, the agricultural residues generated from this production are not processed for energy recovery. Instead, these by-products are typically left to decompose naturally and then reused as organic fertilizers for subsequent cultivation cycles. In this study, potato residues were collected from local crops in northern Ecuador and left in the field for 15 days after harvest and then dried under ambient conditions for 30 days to reduce their moisture content.

Carbonized biomass feedstock was produced through slow pyrolysis, following the MIT-standardized D-Lab charcoal process [22]. The biomass was heated at a rate of 10 °C/min and maintained at 350 °C for 60 min in an oxygen-limited environment to prevent combustion. The process was carried out in a metal kiln with an exhaust system to ensure controlled carbonization as shown in Figure 1a–f. Previously dried potato stalks were introduced into a barrel-type reactor that had been fitted with openings (i.e., biomass inlet) and perforations (i.e., ignition ports) to allow controlled air flow during the pyrolysis process. To facilitate ignition, fragments of the same lignocellulosic material were placed at the base of the reactor. The biomass was ignited, and active combustion was maintained for 10 min. Subsequently, a lid was placed on top of the system, allowing restricted combustion for another 10 min. At the end of this interval, the upper and lower air inlets were completely blocked with sand, and the system was allowed to cool for approximately two hours. As a result of this process, biochar was obtained, which was subjected to a grinding process with a particle size of less than 1 mm. Meanwhile, the non-carbonized biomass feedstock was manually ground to reduce the particle size to approximately 2.5 mm. Subsequently, both types of biomass were sieved to achieve a particle size of less than 1 mm, improving the compaction efficiency [23].

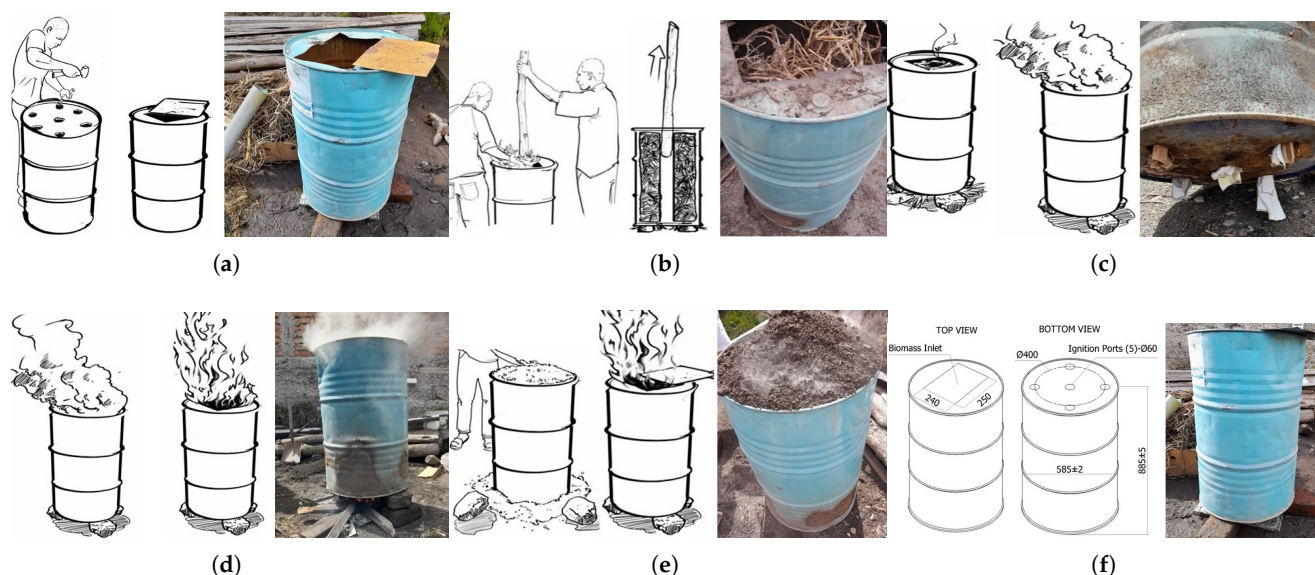


Figure 1. Stages of the biomass pyrolysis process proposed by D-Lab MIT: (a) Reactor suitability. (b) Biomass loading. (c) Biomass ignition. (d) Biomass combustion. (e) Mechanical sealing of air inlets using sand. (f) Reactor dimensions.

The complete biomass preparation process is illustrated in Figure 2. From where two types of biomass were prepared: carbonized biomass (CB) and non-carbonized biomass (NCB).

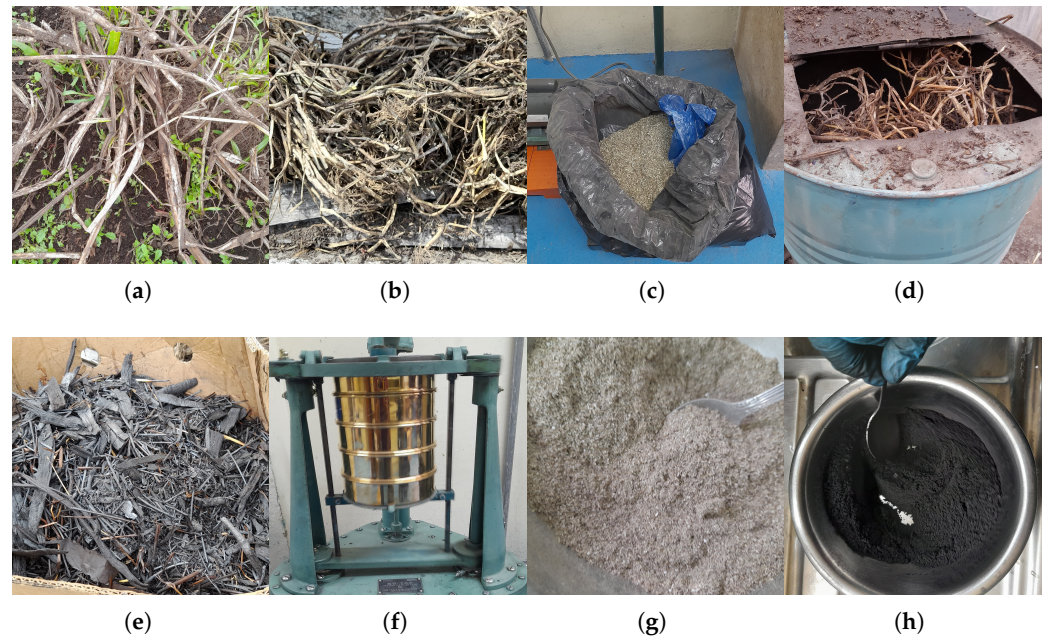


Figure 2. Carbonized and non-carbonized production process: (a) Potato stalks residues. (b) Drying at ambient conditions. (c) NCB feedstock. (d) Pyrolysis process. (e) CB feedstock (f) Grinding and sieving process. (g) Non-carbonized biomass. (h) Carbonized biomass.

2.2. Briquette Production

Briquettes were produced using two vegetable-based binders: potato starch (PS) and achira starch (AS), incorporated at 10% and 20% by weight of biomass to ensure cohesion in the raw material [24]. The mixing process was performed manually for five minutes to achieve homogeneity, with distilled water added in proportions of 60% to 100% by weight [25,26]. Figure 3 shows the process of obtaining the briquetting mixture for carbonized and non-carbonized biomass.

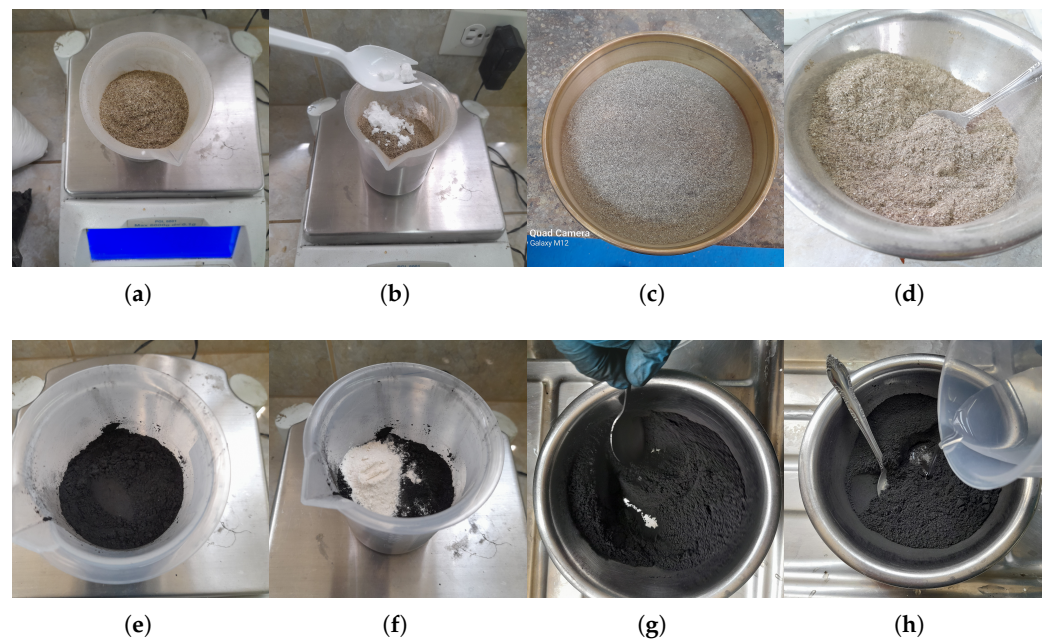


Figure 3. Mixing process for briquetting: (a,e) Measurement of raw material (non-carbonized and carbonized biomass). (b,f) Addition of binders. (c,g) Mixing of components. (d,h) Addition of distilled water and final mixing.

The compaction method presented in Figure 4 was performed using a hydraulic press equipped with a piston-cylinder mechanism, which facilitates the extraction of the formed briquettes. The compaction pressure was set at 10 MPa, maintaining a height-to-diameter ratio of 2:1, as a result, cylindrical briquettes were produced in two sizes: D20/40 and D30/60 mm, with two distinct compaction times: 30 (I) and 60 s (II). Finally, the briquettes were dried in an oven to reduce the moisture content below 10%. Drying was carried out at 60 °C for eight hours, with temperature increases of 5 °C to prevent thermal shock.

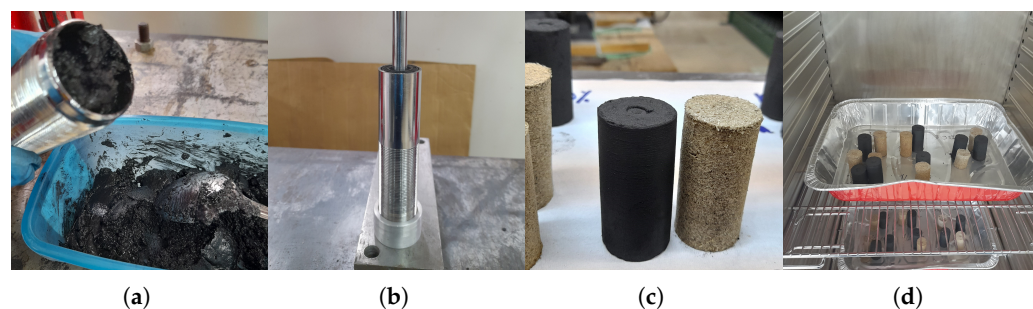


Figure 4. Compaction process for briquetting: (a) Filling of cylinder with biomass mix (carbonized and non-carbonized). (b) Pressing of the mixture. (c) Carbonized and non-carbonized briquettes. (d) Oven-drying.

The specifications of the samples used in this study are summarized in Table 1, in which two commercial types of wood charcoal (WC1 and WC2) and potato stalk (PS) were included as reference samples for comparative analysis during characterization.

Table 1. Designation of characterized samples.

Biomass Type	Designation	Binder Fraction (%)	Compaction Time (s)
Carbonized	CB-PS10-I	10	30
	CB-PS10-II	10	60
	CB-PS20-I	20	30
	CB-PS20-II	20	60
	CB-AS10-I	10	30
	CB-AS10-II	10	60
	CB-AS20-I	20	30
	CB-AS20-II	20	60
Non-Carbonized	NCB-PS10-I	10	30
	NCB-PS10-II	10	60
	NCB-PS20-I	20	30
	NCB-PS20-II	20	60
	NCB-AS10-I	10	30
	NCB-AS10-II	10	60
	NCB-AS20-I	20	30
	NCB-AS20-II	20	60
Carbonized	CB-PS35-II	35	60
	CB-PS50-II	50	
	CB-AS35-II	35	
	CB-AS50-II	50	
Non-Carbonized	NCB-PS35-II	35	60
	NCB-PS50-II	50	
	NCB-AS35-II	35	
	NCB-AS50-II	50	
	PS	—	
Carbonized	WC1	—	—
	WC2	—	—

2.3. Scanning Electron Microscopy (SEM)

Carbonized biomass samples were prepared with a flat surface and an approximate diameter of 1 mm to facilitate imaging. However, non-carbonized biomass samples exhibited low visibility under the microscope because of their low conductivity. To improve observation, a thin gold coating was applied to improve conductivity, allowing better electron flow during imaging and following standard SEM sample preparation procedures [27]. Microstructural analysis was performed using a PSEM eXpress scanning electron microscope (Aspex Corporation, Reston, VA, USA) with a detection range of 500 to 5 mm. Micrographs were taken under the following conditions:

- Accelerating voltage: 10 kV and 5 kV;
- Filament loading: 70.2%;
- Magnifications: 100X, 500X, and 1500X;
- Imaging mode: Standard conditions were applied to optimize contrast and resolution.

2.4. Raman Spectroscopy

It was used to characterize the carbonaceous structure of the carbonized briquettes; the samples were prepared in powder form to ensure uniform analysis conditions. To enhance the representativeness of the results, we collected spectra from two randomly selected points on each sample, providing an overall assessment of their structural and chemical properties. A Raman spectrometer (Horiba Scientific, Kyoto, Japan) was used for the analysis under the following conditions:

- Excitation source: 532 nm laser wavelength;
- Laser power: 50 mW;
- Objective lens: 50X magnification;
- Focal aperture: 100 μm .

2.5. Thermogravimetric Analysis (TGA)

The primary objective of TGA was to evaluate the average moisture content after the sample drying process to verify if it was within the target range 10%, which is ideal to obtain characteristic calorific values suitable for a promising biofuel [24,28]. The TGA curves were analyzed to identify the different stages of thermal decomposition corresponding to moisture evaporation, volatile matter release, and fixed carbon content. The experiments were carried out using a Q-500 Thermogravimetric analyzer (TA Instruments, New Castle, DE, USA) under the following conditions:

- Sample weight range: 5–30 mg;
- Temperature range/heating rate: 25–700 $^{\circ}\text{C}$: 5 $^{\circ}\text{C}/\text{min}$;
- Atmosphere: Inert nitrogen gas at 50 mL/min to both the sample and the microbalance.

2.6. Compression Test

According to the procedure described in ASTM C39/C39M-21, samples were prepared with a height-to-diameter ratio of 2:1 to ensure consistency in mechanical evaluation [29]. The test was conducted until the carbonized briquettes fractured or the non-carbonized briquettes reached 20% deformation. To improve the reliability of the data, three measurements were made per sample to minimize the standard deviation of the results. The test was performed on a universal testing machine H25KS (Tinius Olsen, Horsham, PA, USA) designed for the compression testing of composite materials, at a controlled loading rate of 0.25 MPa/s $\pm$ 0.05 MPa/s (maximum load capacity: 25 kN; force precision: 0.01 N). The RCW-800 thermohygrometer (Elitech Technology, San Jose, CA, USA) (temperature resolution/relative humidity resolution: 0.1 $^{\circ}\text{C}$ /0.1%) was used to measure and record

environmental conditions during the tests. The recorded environmental conditions ensured the consistency and repeatability of the test, allowing an accurate assessment of the mechanical properties of the briquettes.

2.7. Thermal Characterization

The higher heating value (HHV) of the samples, including carbonized and non-carbonized briquettes, commercial wood charcoal, and potato stalks, was determined using a 6400 bomb calorimeter (Parr Instrument Company, Moline, IL, USA). The procedure followed BS EN 14918: 2009 [30], which specifies the methodology for determining the gross calorific value of solid biomass using a bomb calorimeter. Where necessary, moisture content values obtained from thermogravimetric analysis (TGA) were incorporated to ensure the precision of the results.

3. Results and Discussion

3.1. Morphology

Scanning electron microscopy (SEM) was used to study the morphology of carbonized and non-carbonized briquettes. The analysis focused on non-carbonized briquettes, specifically those obtained from fractions of achira and potato binder weight, coded as NCB-AS35-II, and NCB-PS35-II revealed that the binder particles have a hemispherical shape, as shown in Figure 5. The average particle diameter was 51.33 μm for NCB-AS35-II and 41.05 μm for NCB-PS35-II. In addition, the SEM images suggest that significant binder-based adhesion cannot be conclusively confirmed because the binder particles appear to be dispersed rather than uniformly integrated into the matrix.

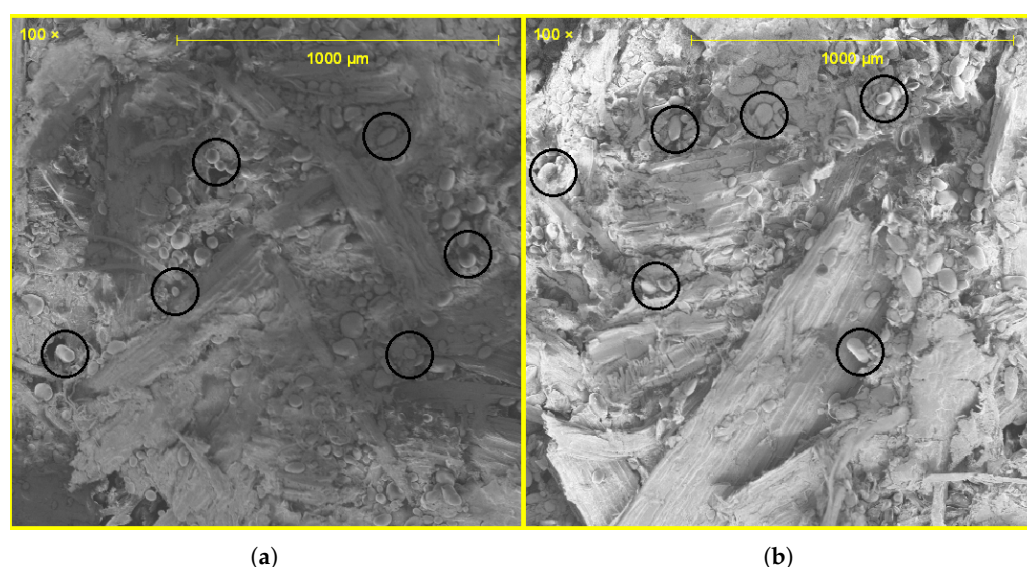


Figure 5. SEM micrograph at 100X: (a) NCB-AS35-II with achira binder particle. (b) NCB-PS35-II with potato binder particle.

Porosity is a key parameter that significantly influences the combustion performance of briquettes [31]. According to IUPAC, pores are classified into three categories according to their size: micropores (<2 nm), mesopores (2–50 nm), and macropores (>50 nm) [32]. Figure 6a,b show SEM micrographs of the CB-PS10-I and CB-AS10-I samples, respectively, where macropores are visible along with the presence of the binder on the surface. When comparing these images with the WCI and WCII samples shown in Figure 6c,d, an increase in macropore size is observed. This is a crucial characteristic of high-calorific-value biofuels, as higher porosity enhances combustion efficiency, provided that moisture levels are

reduced to near 0%. Otherwise, excessive macroporosity can lead to greater moisture retention, which ultimately reduces the calorific value of the biofuel [31,33].

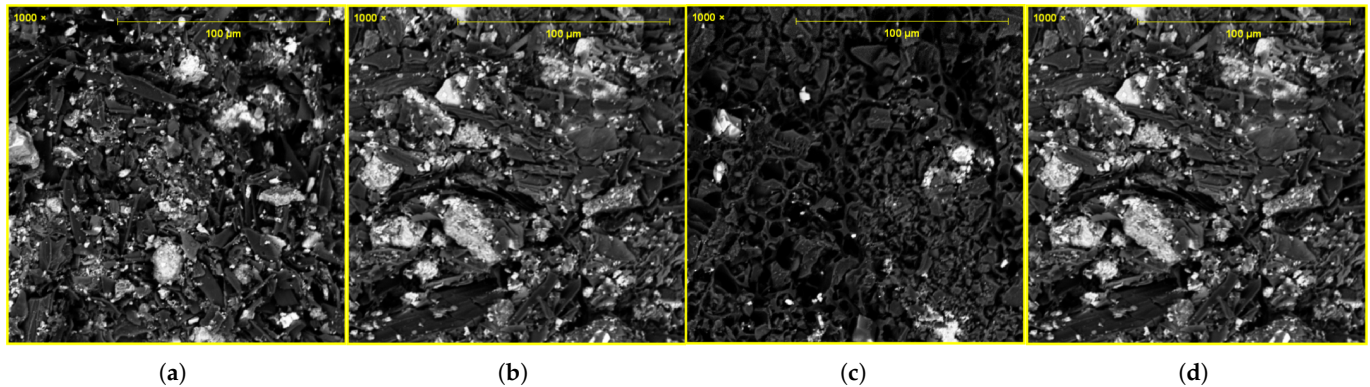


Figure 6. Sample surface porosity at 1000X: (a) CB-PS10-I. (b) CB-AS10-I. (c) WCI. (d) WCII.

In the briquetting process, the compaction time is a critical factor influencing the structural integrity and performance of the final product [24]. Figure 7 presents micrographs of four carbonized briquettes produced with two different compaction times: 30 and 60 s. Micrographs (a)–(d) correspond to compacted briquettes for 60 s at a magnification of 100X, showing a uniform and well-consolidated surface. In contrast, micrographs (e)–(h), which depict compacted briquettes for 30 s at the same magnification, reveal noticeable surface cracks (indicated by blue arrows). These cracks suggest insufficient compaction, which can lead to lower mechanical strength and increased fragility [23].

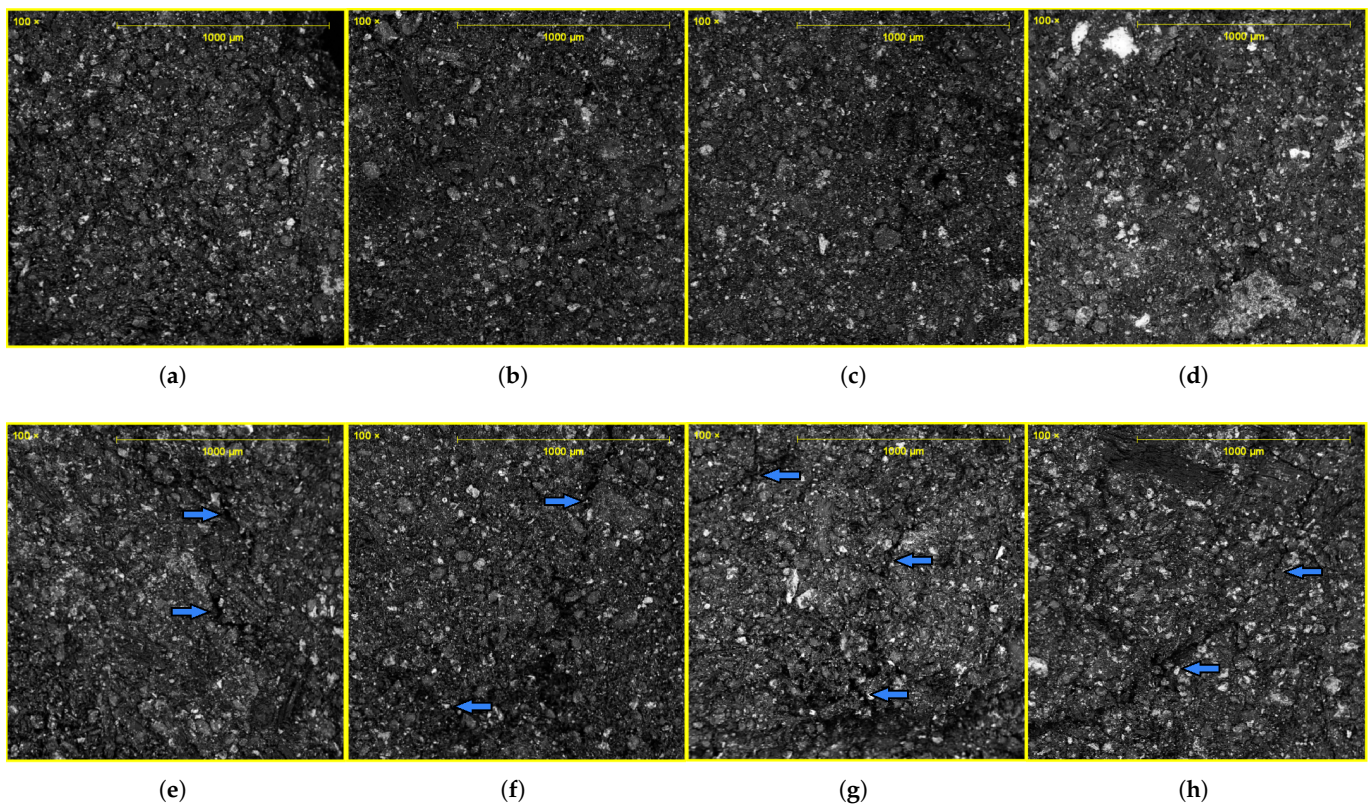


Figure 7. Micrographs at different compaction times: (a) CB-PS20-II. (b) CB-PS10-II. (c) CB-AS20-II. (d) CB-AS10-II. (e) CB-PS20-I. (f) CB-PS10-I. (g) CB-AS20-I. (h) CB-AS10-I.

Extending the compaction time enhances the briquette density and strengthens the cohesion between the base material particles while improving adhesion with the binder.

Compaction times reduce porosity and increase mechanical strength, directly affecting the combustion efficiency of briquettes [23]. Moreover, briquettes with low compaction times tend to disintegrate more quickly under combustion conditions, leading to inefficient burning and higher emissions [34,35].

3.2. Carbon Formation

The collected spectra shown in Table 2 were used to assess the presence of characteristic Raman bands, particularly the D band (1350 cm^{-1}) and the G band (1580 cm^{-1}), which provide information on the degree of disorder and graphitization of the carbonaceous material. The intensity ratio I_D/I_G was determined to evaluate the structural ordering of carbon in the samples [36].

Table 2. I_D/I_G intensity ratios of carbonized and charcoal samples.

Sample	Parameter	D-Band	G-Band	I_D / I_G
CB-PS10-II	Position (cm^{-1})	1328.68	1585.04	0.91
	Intensity ($\mu.a$)	0.90701	1	
CB-PS20-II	Position (cm^{-1})	1350.79	1594.29	0.80
	Intensity ($\mu.a$)	0.79632	1	
CB-PS35-II	Position (cm^{-1})	1356.06	1589.67	0.78
	Intensity ($\mu.a$)	0.77500	1	
CB-PS50-II	Position (cm^{-1})	1357.13	1589.67	0.70
	Intensity ($\mu.a$)	0.70363	1	
CB-AS10-II	Position (cm^{-1})	1352.18	1589.67	0.76
	Intensity ($\mu.a$)	0.76442	1	
CB-AS20-II	Position (cm^{-1})	1353.76	1592.57	0.81
	Intensity ($\mu.a$)	0.81187	1	
CB-AS35-II	Position (cm^{-1})	1360.10	1592.57	0.75
	Intensity ($\mu.a$)	0.74644	1	
CB-AS50-II	Position (cm^{-1})	1334.84	1584.85	0.82
	Intensity ($\mu.a$)	0.82092	1	
WCI	Position (cm^{-1})	1376.13	1595.83	0.72
	Intensity ($\mu.a$)	0.72097	1	

The G band is associated with the formation of amorphous graphite, while the D band is characteristic of carbonized briquettes containing amorphous carbon [37]. The I_D/I_G intensity ratio is an indicator of structural disorder; lower values indicate fewer defects and higher structural order. When this ratio approaches 1, it indicates a reduction in sp_2 bonds between carbon atoms, which means increased disorder in the carbon structure [38]. Furthermore, the D and G peaks in the Raman spectra correspond to sp_2 configurations where the G bonds exhibit stretching vibrations [39]. As shown in Table 2, the I_D/I_G ratios of the carbonized briquettes are higher than those of the commercial charcoal, indicating a greater number of defects and a reduction in sp_2 bonds. These differences are attributed to the carbonization process and variations in particle size [38]. These results indicate that the presence of amorphous carbon in biochar leads to a higher intensity of the D band compared to the G band, resulting in increased I_D/I_G ratios [40]. The elevated I_D/I_G values observed in the carbonized briquettes suggest a material with a lower degree of graphitization, which could affect its thermal and electrical conductivity.

Additionally, the type and weight percentage of the binders, as well as the compaction time, did not result in significant structural differences between carbonized briquettes and charcoal briquettes. However, the I_D/I_G ratio of the carbonized briquettes indicates a

higher number of defects and a decrease in sp_2 bonds, a phenomenon attributed to both the carbonization process and variations in particle size. This behavior is consistent with previous studies that correlate an increase in disorder with the formation of amorphous carbon [24].

In this study, the CB-PS10-II briquettes, which contained a low percentage of potato binder and underwent a compaction time of 60 s, deviated from the expected trend, showing a higher content of amorphous carbon. Meanwhile, briquettes coded as CB-PS35-II, CB-PS50-II, CB-AS35-II, and CB-AS50-II exhibited I_D/I_G ratios ranging from 0.70 to 0.82, a range that is highly characteristic of amorphous carbon [24,41]. These findings suggest that binder concentration and compaction time play a crucial role in the structural organization of the material, potentially influencing its mechanical stability and combustion properties.

3.3. Thermal Decomposition

The TGA analysis provided key information on the thermal behavior of biofuels, identifying three fundamental characteristics: moisture content, the release of volatile compounds during pyrolysis, and the formation of fixed carbon, which results from the thermal decomposition of hemicellulose, cellulose, and lignin [42]. As illustrated in Figure 8, three expected thermal regions during the pyrolysis stage for a potato stalk sample were identified as follows:

- Moisture evaporation (0 °C–190 °C).
- Volatile matter decomposition (190 °C–380 °C).
- Charcoal zone (380 °C–700 °C).

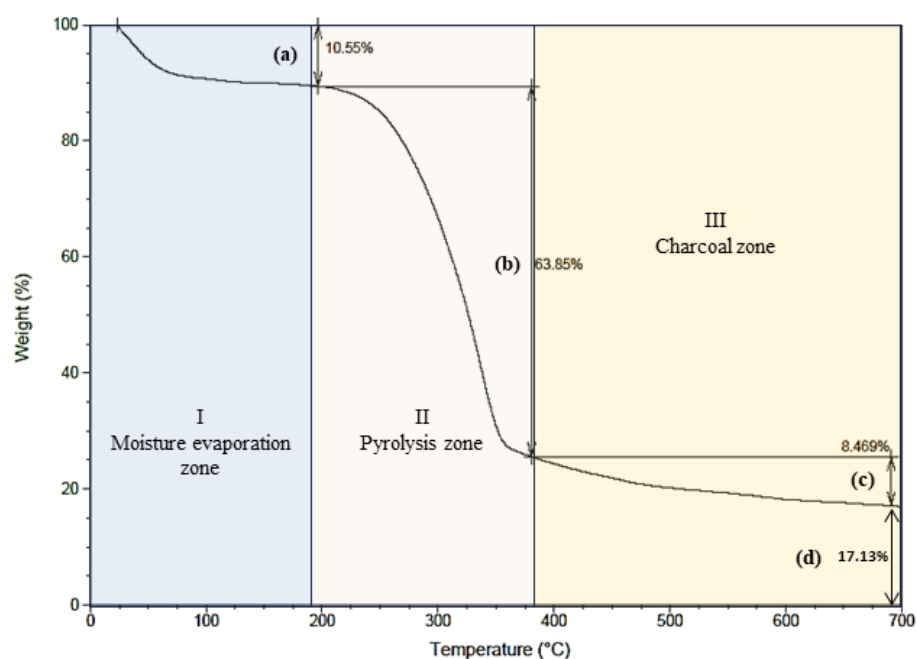


Figure 8. Potato stalk TGA curve. (a) Moisture content: 10.55%. (b) Cellulose, hemicellulose, and part of the lignin content: 63.85%. (c) Lignin and thermally resistant materials content: 8.4%. (d) Fixed carbon content: 17.13%.

The results presented in Table 3 highlight key aspects of the thermal characterization of the samples. The moisture content of non-carbonized briquettes, carbonized briquettes, and potato stalk samples is approximately $10.0\% \pm 3$, which falls within the expected range for biofuels [24,26,28,41]. At 700 °C, the charcoal zone in non-carbonized briquettes is approximately 30% in all samples analyzed, suggesting that almost one third of the material could be used as commercial charcoal, enhancing its potential as a solid biofuel [43].

The volatile matter content varies significantly between samples, with non-carbonized briquettes containing around 57.38%, while carbonized briquettes exhibit a lower 14.22% on average, indicating a more stable structure in carbonized briquettes [44,45]. Furthermore, the potato stalk sample shows the highest volatile content at 63.85%, due to the absence of a binder, resulting in a higher proportion of hemicellulose and cellulose, both of which decompose during the pyrolysis stage [45].

Table 3. Results of TGA analysis on carbonized and non-carbonized briquettes.

Sample	Moisture Evaporation (%)	Volatile Matter (%)	Lignin and Thermally Resistant Materials (%)	Fixed Carbon (%)
NCB-PS10-II	12.35	57.58	9.49	20.58
NCB-PS20-II	12.14	58.50	9.08	20.28
NCB-AS10-II	13.32	57.19	10.72	10.77
NCB-AS20-II	13.06	56.26	9.23	21.45
CB-PS10-II	7.55	11.60	5.85	69.11
CB-PS20-II	7.73	17.31	5.55	69.41
CB-AS10-II	7.69	11.81	6.60	73.9
CB-AS20-II	7.89	18.16	4.53	69.42
PS	10.55	63.85	8.47	17.13

Table 4 compares the results obtained for PS and NCB-AS10-II briquettes with those of other primary agricultural residues commonly used in briquette production. The moisture content observed in the PS and NCB-AS10-II samples is remarkably high, almost twice that of most other waste materials. The high moisture content present in the biomass negatively affects the combustion efficiency, as it requires additional energy to evaporate the water before effective combustion can begin. This energy expenditure results in reduced net heat production, which decreases the overall energy efficiency of the fuel. In addition, high moisture levels are associated with incomplete combustion, resulting in increased carbon monoxide (CO) and particulate emissions. Consequently, to improve the performance of biomass combustion, it is imperative to reduce moisture, as it has a direct relationship with energy efficiency and environmental emissions [46,47].

In contrast, the amount of volatile matter is reduced, indicating a lower cellulose content within these materials. Cellulose serves as a fundamental constituent that significantly influences energy release during the combustion process. A reduced cellulosic content can lead to a reduction in the energy released during biomass combustion, which consequently affects its overall effectiveness as a biofuel [47]. Finally, both PS and NCB-AS10-II briquettes have a higher fixed carbon content, which improves their manufacturing efficiency and thermal conversion performance with values comparable to those of rice husk and wood branch, respectively. This property, combined with an optimal moisture level, improves the durability and calorific value of briquettes [46,47].

Table 4. Reference values for thermal decomposition of different residues used as biofuels.

Sample	Moisture Evaporation (%)	Volatile Matter (%)	Fixed Carbon (%)	Reference
PS	10.55	63.85	17.13	–
NCB-AS10-II	13.32	57.19	10.77	–
Wheat husk	5.98	69.19	12.72	[48]
Rice husk	4.65	68.89	17.17	[48]
Corn straw	6.10	76.00	13.20	[49]
Wheat straw	4.39	67.36	19.32	[49]
Wood branch	4.39	82.96	10.51	[49]
Torrefied pelletized sawdust	5.50	75.60	24.00	[50]

3.4. Compression Strength

As shown in Table 5, the carbonized sample CB-PS10-I exhibits a higher compressive strength than other carbonized briquettes, demonstrating that effective mechanical strength can be achieved even with binder percentages below 15%, or without binder (0%), due to the lignocellulosic properties of the residue that self-bind [18,34]. However, non-carbonized briquettes exhibited superior compressive strength with peak values of 1.70 MPa for NCB-AS20-II and 1.78 MPa for NCB-AS20-I, outperforming comparable biofuels derived from rice husk and African palm residues [51].

Table 5. Carbonized and non-carbonized briquette compression test results.

Sample	Load (N)	Strength (MPa)
CB-PS10-I	30.00	0.09
CB-PS20-I	11.11	0.03
CB-AS10-I	11.94	0.03
CB-AS20-I	10.28	0.03
CB-PS10-II	25.28	0.07
CB-PS20-II	18.33	0.05
CB-AS10-II	19.45	0.05
CB-AS20-II	16.11	0.05
NCB-PS10-I	446.90	1.35
NCB-PS20-I	426.05	1.30
NCB-AS10-I	420.84	1.28
NCB-AS20-I	566.47	1.70
NCB-PS10-II	368.36	1.10
NCB-PS20-II	436.88	1.39
NCB-AS10-II	513.93	1.55
NCB-AS20-II	582.39	1.78

Carbonized briquettes generally exhibited lower ultimate loads and stresses than their non-carbonized counterparts, although no significant differences were observed between the potato-based (PS) and achira-based (AS) binders due to their similar compositions. For non-carbonized briquettes, a 20% starch content marginally improved the loads and maximum stresses compared to 10% starch, although this trend was absent for carbonized samples. In addition, briquettes compacted for 60 s exhibited slightly higher mechanical strength than those processed for 30 s, suggesting that extended compaction time improves the integrity of the sample [34]. It is important to note that lignin acts as a natural binder and that its reduction causes a decrease in particle cohesion. This fact, along with the small cracks observed in the SEM micrographs (Figure 7e–h), contributes to the decrease in the compressive strength of the carbonized briquettes.

3.5. Higher Heating Value

The higher heating value of the briquettes presented in Table 6, composed mainly of residues from the potato stalks, ranged from 12 MJ/kg to higher, confirming their suitability as biofuels [48,49,52]. Non-carbonized briquettes exhibited calorific values comparable to those of their feedstock (i.e., potato stalk) while offering the practical advantage of being preprocessed by pressing and binding.

Although carbonization did not significantly improve the energy content of these briquettes, the marginal increase observed is consistent with the trends reported for other residues, such as sugarcane bagasse, rice husk, and coconut husk, where carbonization improves calorific values more significantly [7,49]. In particular, carbonized samples only slightly outperformed non-carbonized ones. Neither starch content (<35%) nor binder type (PS or AS) significantly affected calorific values, as evidenced by the negligible maximum

difference of 1.24 MJ/kg between samples [53]. The compaction time had a minor effect: briquettes compacted for 60 s (II) had slightly lower calorific values than those compacted for 30 s (I), probably due to density variations from prolonged compaction [41].

Table 6. Higher heating values for different carbonized and non-carbonized samples.

Sample	Higher Heating Value (MJ/kg)	Sample	Higher Heating Value (MJ/kg)
CB-PS10-I	15.03	NCB-PS10-I	15.22
CB-PS10-II	15.76	NCB-PS10-II	15.16
CB-PS20-I	15.52	NCB-PS20-I	15.08
CB-PS20-II	15.52	NCB-PS20-II	15.20
CB-AS10-I	15.40	NCB-AS10-I	15.07
CB-AS10-II	14.52	NCB-AS10-II	14.99
CB-AS20-I	15.26	NCB-AS20-I	14.98
CB-AS20-II	15.31	NCB-AS20-II	14.95
CB-PS35-II	15.04	NCB-PS35-II	14.96
CB-AS35-II	14.96	NCB-AS35-II	15.09
PS	15.44	WCI	30.48

For comparative analysis, Table 7 shows the high heating values of carbonized and non-carbonized briquettes, potato stalks, and other solid biofuel feedstocks. The evaluated briquettes have specific heating values comparable to those of common agricultural residues such as rice hulls and corn straw. However, their energy potential is 16.4% lower than that of sugarcane bagasse, a high-demand feedstock known for its superior energy content [49].

Table 7. High heating values for other types of residues.

Sample	Higher Heating Value (MJ/kg)	Reference
CB-PS10-II	15.76	–
NCB-PS10-II	15.22	–
PS-AS10-II	15.44	–
Bamboo fiber	18.15	[48]
Sugarcane bagasse	18.47	[48]
Rice husk	13.38	[7]
Corn cob	15.23	[7]
Paper	14.00–18.24	[54,55]
Food waste	17.53	[56,57]

To obtain more reliable results in biomass carbonization, it is essential to carefully control the pyrolysis parameters, such as the calcination time, temperature, and oxygen absence. These processes can be carried out using semiautomatic methods to ensure greater precision and reproducibility. In addition, it is recommended to explore densification techniques, such as screw extrusion, roller pressing, and pelletizing, applied to blends to produce briquettes while maintaining a temperature control between 60 °C and 140 °C. This range promotes better adhesion between the binder and the base material, thereby improving the energy quality and resistance of the obtained briquettes.

4. Conclusions

This work shows that residues derived from the potato stalk can be efficiently transformed into quality solid biofuels, offering a sustainable substitute for traditional charcoal manufacture. The CB-PS10-II and NCB-PS10-I briquettes showed remarkable characteristics for use as biofuels, with calorific values of 15.76 and 15.22 MJ/kg, respectively, exceeding the minimum feasibility threshold of 12 MJ/kg for biofuels, along with an optimal mois-

ture content ($10 \pm 3\%$) and high compressive strength with only the 10% binder included. Although carbonization produced minor improvements in energy content, non-carbonized briquettes proved to be more efficient, particularly when subjected to a 60 s compaction duration to improve structural uniformity. In particular, the use of potato stalks, which is an abundant resource in agricultural areas of Ecuador, coupled with sustainable production techniques, i.e., with minimal use of the binder and no carbonization, represents a circular economy strategy that has the potential to reduce the indiscriminate use of forest resources. Although the energy yield remains below that of commercial charcoal 30.48 MJ/kg, this approach demonstrates how agricultural by-products can be upgraded to environmentally friendly biofuels through optimized, low-impact production processes.

Future works could evaluate scalability, cost-effectiveness, and life cycle analysis with a more automated and large-scale production process in mind. These analyses could reduce the gap between the calorific value obtained and that of commercial coal. However, the focus of this study was on aspects such as technologies accessible to farmers, use of local raw materials, and, mainly, the ideology of the circular economy.

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Abbreviations

The following abbreviations are used in this manuscript:

CB	Carbonized Biomass
NCB	Non-Carbonized Biomass
WC	Wood Charcoal
PS	Potato Stalk
SEM	Scanning Electron Microscopy
TGA	Thermogravimetric Analysis
HVV	Higher Heating Value
ASTM	American Society for Testing and Materials
IUPAC	International Union of Pure and Applied Chemistry

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