ISSN: 2224-0616
Int. J. Agril. Res. Innov. Tech. 16(1): 87-95, June 2026
DOI: https://doi.org/10.3329/ijarit.v16i1.92283
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Available online at https://ijarit.online
https://www.banglajol.info/index.php/IJARIT

Production and thermophysico-chemical characterization of charcoal briquettes from anaerobic fermentation digestate

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Received 3 March 2026, Revised 15 May 2026, Accepted 24 June 2026, Published 30 June 2026

ABSTRACT

Wood energy valorization dominates and accelerates deforestation with negative consequences for climate change. To reduce pressure on forests and mitigate climate change, this study proposes a sustainable solution aimed at producing ecological charcoal briquettes from digestates derived from cow dung and *Titonia diversifolia*. For this purpose, digestates from a 45-day mesophilic anaerobic co-digestion were dried to 8% moisture content over 35 days. The dried digestates were then submitted to uncontrolled pyrolysis. The parallelepiped and the cylindrical charcoal briquette were produced and tested. The results are as follows: the maximum pyrolysis temperature reached 390°C. The produced biochar was compressed into parallelepiped and cylindrical briquettes. Physicochemically, no difference between the two shapes was observed. Thermally, the heating value of the cylindrical and parallelepiped briquettes was 19 kJ/kg. Practically, the cylindrical shape, although less energy-efficient per unit of time, offers better heat utilization efficiency (a greater amount of water evaporated for an equivalent mass consumed), while the parallelepiped shape is characterized by higher instantaneous power, but with greater heat losses to the environment. Finally, optimizing the geometry and pressing of briquettes is essential to improving the efficiency and sustainability of biofuels, particularly in low-resource artisanal contexts.

Keywords: Climate change, Pyrolysis, Anaerobic codigestion, Charcoal briquettes, Shape, Digestate

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Cite this article as: Kemgou Woumfo, K.G., Jospin, T.G., Tchoumboue, N. and Grisseur, D.H. 2026. Production and thermophysico-chemical characterization of charcoal briquettes from anaerobic fermentation digestate. *Int. J. Agril. Res. Innov. Tech.* 16(1): 87-95. https://doi.org/10.3329/ijarit.v16i1.92283

Introduction

Energy demand in developing countries is growing rapidly due to population growth and economic expansion, with a nation's energy consumption profile reflecting its socio-economic level (Tanyi *et al.*, 2023; Gebrezgabher *et al.*, 2025). To meet these growing needs, fossil fuels such as oil, coal, and natural gas remain widely used (Ngosong *et al.*, 2024). However, these resources are limited, and their exploitation has significant environmental impacts. Actually, the world is facing high CO_2 emissions, contributing to an estimated increase in global temperature of 2.4-2.8°C by 2100 (Friedlingstein *et al.*, 2023). The intensive use of coal, kerosene, and petroleum in heat production and transportation industries contributes significantly to these emissions, while high production costs often make these resources inaccessible to developing countries (Shittu, 2024). In many developing countries, limited access to expensive alternative energy sources leads people to focus on biomass, a local, abundant, and renewable resource available close to rural areas (Babayomi, 2022; Nguyen *et al.,* 2024). In Cameroon, approximately 226.9 million tons of agricultural residues and 22.5 million hectares of forest are available each year (Tanyi *et al.,* 2023; Fokeng, 2020), making biomass the primary source of energy for cooking and heating (Kouer, 2023). However, the lack of control over cutting schedules and the physical and chemical composition of biomass limit its energy efficiency and lead to negative environmental and health impacts, such as deforestation and exposure to smoke and fine particles, which are responsible for respiratory diseases and lung infections (Elbayoumi, 2023; Chowdhury, 2025; Sheikh Ali, 2024).

Furthermore, in the context of a circular economy, the recovery of by-products from processes such as anaerobic codigestion of digestates helps reduce environmental pollution and optimize resource use for more significant economic purposes. Indeed, digestates from anaerobic codigestion are widely used in agricultural production as organic fertilizers, and extensive research has established conclusive evidence of their contribution to agricultural yields. Although anaerobic digestion (AD) digestates are used in agriculture, they are also a source of biomass for producing coal briquettes. Charcoal briquette production is a promising, relatively recent technology used in rural areas of developing countries, particularly in Cameroon (Sharma *et al.,* 2015).

Recovering this AD digestate through pyrolysis could be a sustainable and effective solution. This thermochemical process, carried out in the absence or with very low oxygen levels at temperatures between 300 and 700°C, enables the production of biochar, bio-oil, and synthesis gas (syngas) (Sheikh Ali, 2024). The proportions of these products depend on several parameters, such as temperature, residence time, and heating rate: rapid pyrolysis at high temperatures promotes the production of bio-oil, whereas slow pyrolysis at moderate temperatures favors the formation of biochar (Irfan *et al.,* 2016). Charcoal briquettes are very useful for economic purposes (meat and fish charcoal traders, agroindustries combustion) and social purposes (households). Briquettes are safer for the environment than the raw materials used in the combustion process (Nzali *et al.,* 2023; Zhao *et al.,* 2018). The optimal shape of charcoal briquettes remains a topic of discussion among researchers. Numerous studies have explored the manufacture of briquettes from various types of biomass: alfa (Debdoubi *et al.,* 2005) sesame stalk and coconut shells, rice straw (Gebrezgabher *et al.,* 2025; Panwar *et al.,* 2011), corn meal and rice husks and Jatropha seed cakes (Oladeji, 2010; Nsah-ko Tchoumboué *et al.,* 2020) mango leaves, eucalyptus leaves, sawdust and banana leaves (De Oliveira Maia *et al.,* 2014), as well as certain forest species such as *Arundinaria alpina* and *Prosopis juliflora* (Feleke *et al.,* 2020). Other studies have shown the effectiveness of sawdust (Kouakou and Emeruwa, 2020) or mixtures based on coffee husks and bagasse (Lubwama and Yiga, 2018). The results obtained by each of these studies remain satisfactory and applicable. Very little research has focused on the use of digestates from anaerobic digestion on the one hand, and on comparing briquette shapes based on their density, stability, combustion efficiency, and the energy consumption associated with their production. Yet this variable could be decisive in optimizing the energy and economic performance of briquetting. Ultimately, optimizing the geometry and pressing of briquettes is essential to improving the efficiency and sustainability of biofuels, particularly in low-resource artisanal contexts.

The main objective of this work is to produce and characterize charcoal briquettes physically, chemically, and thermally from AcoD digestates.

Materials and Methods

Digestate obtention and processing

Digestates were obtained from an anaerobic co-digestion reactor treating cow manure and Tithonia diversifolia in a 50:50 ratio (dry matter), with an HRT of 45 days. The raw digestate, with a moisture content of 90%, was dried in a dryer at 30°C for 35 days. The final moisture content of the digestate was 8%, which was less than 15%, ensuring an efficient thermochemical process (Faaij, 2013; Mata-Alvarez *et al.,* 2014). A total mass of dried digestate was 5.2 kg.

Briquette production

Biochar production

Biochar was produced based on methods developed by Bridgwater (2012). In fact, 5.2

kg of dried digestate was pyrolyzed in a homemade double-chamber pyrolyser with a capacity of 72 liters (Figure 1). Low-rate pyrolysis was carried out. The woody stems of *Tithonia diversifolia* were used as fuel for pyrolysis. The temperature change inside the pyrolyser was monitored using an HT-9815 digital thermocouple (range: 0–1000°C; accuracy: ± 1°C). The total duration of the process was recorded using a stopwatch from ignition to the end of carbonization. At the end of pyrolysis, the biochar was left to cool, then collected and ground to a powder with a particle size of 0.001 millimeters.

The pyrolysis key parameters were as follows:

Heating rate (HR) was determined using equation 3

$$HR = \frac{\text{Average pyrolysis temperature}}{\text{Pyrolysis duration}} \quad (3)$$

Average pyrolysis temperature in °C; Pyrolysis duration in hours (h); Heating rate in °C/h

Biochar yield was determined using equation 4

$$\text{Biochar yield} = \frac{\text{biochar mass}}{\text{digestate mass}} \times 100 \quad (4)$$

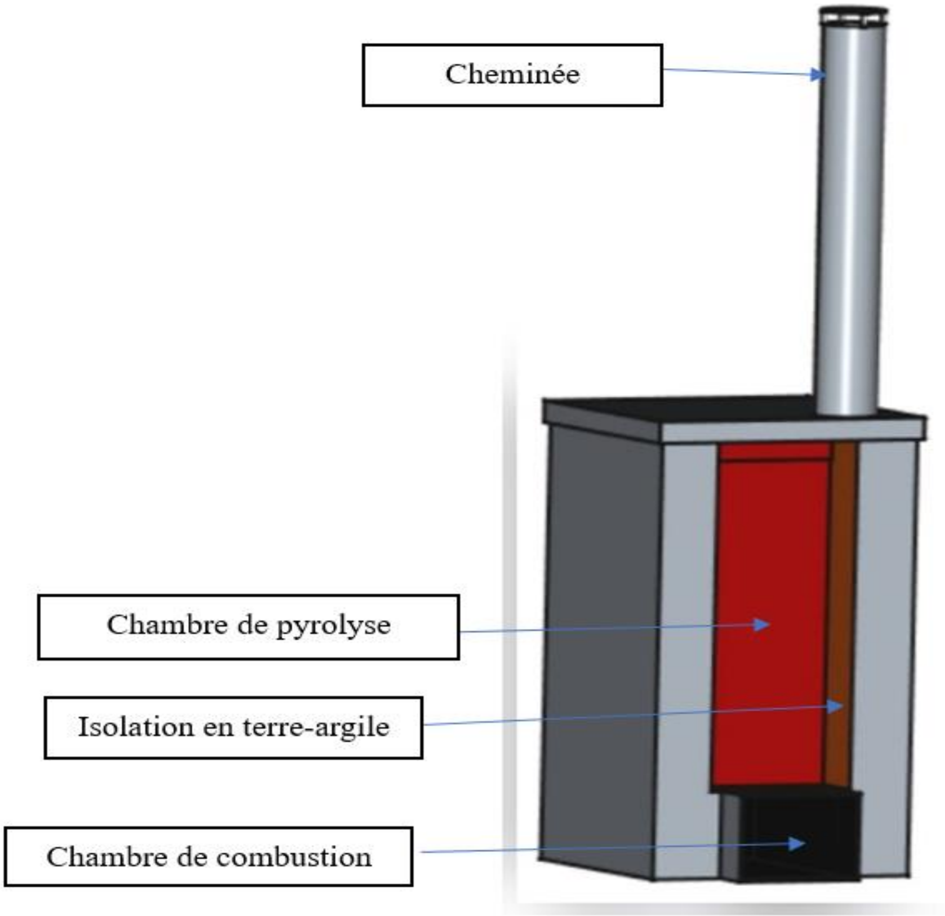
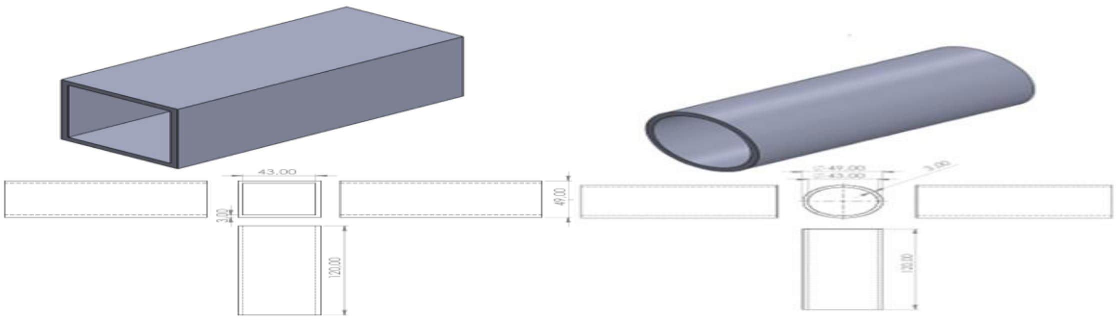


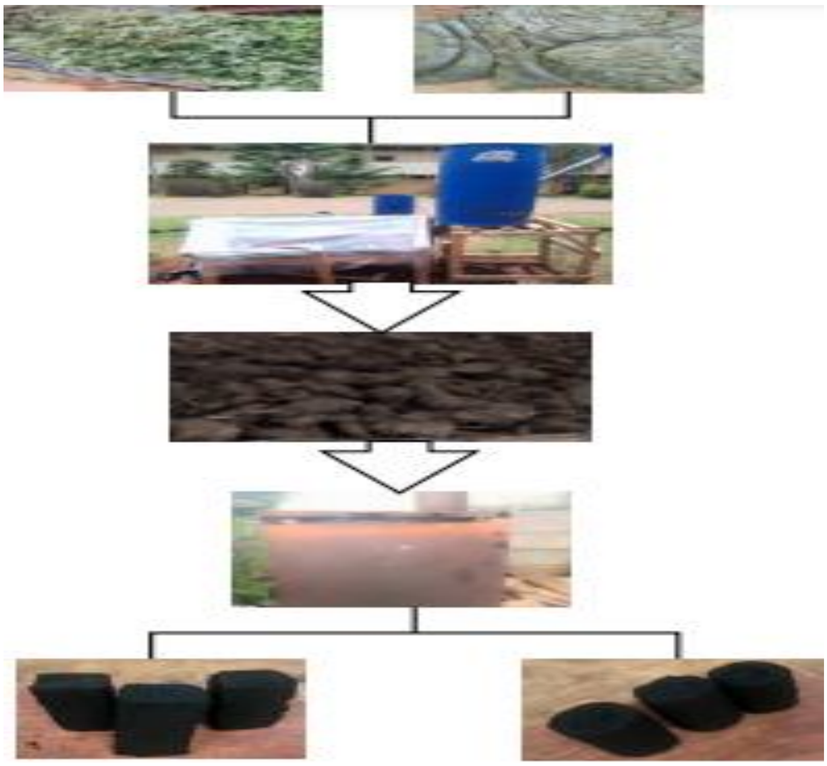
Fig. 1. Pyrolysis reactor and its compartments.

Briquettes shape design

The above biochar powder was submitted to two types of shapes, the parallelepiped and the cylindrical. For this purpose, the moulds corresponding to the above shapes were designed and characterized as 4.3 cm × 3.5 cm × 4.3 cm and 4.3 cm diameter for the parallelepiped and the cylindrical shapes, respectively (Figure 2). These dimensions were selected based on previous studies (Tanyi *et al.,* 2023). The biochar was mechanically mixed with a binder made up of cassava flour and water (Rivera *et al.,* 2021) at a ratio of 1:0.05:0.5 in mass (kg). The mixture was introduced into the moulds and then submitted to a mechanical press producing 13 MPa. After demoulding, the obtained shaped briquettes were dried for 24 hours at 22°C in an oven at 105°C (Jama *et al.,* 2000; Bot, 2022) to reach a moisture content of 5%.



a



b

Fig. 2. a) Briquette shape moulds b) Briquettes' production process.

Characterization of briquettes

Physical characterization

The physical characterization of the briquettes involved measuring their length, width, and thickness. The measurement was done using the digital vernier caliper.

Chemical characterization

The chemical characterization consisted of determining the moisture content (MC), the volatile matter (VM), and the fixed carbon content (FCC) given by equations 5, 6, and 7, respectively.

$$H(\%) = \frac{M_{wet} - M_{105°C}}{M_{wet}} \times 100 \quad (5)$$

H(%): Moisture content (%); M_{wet} : Mass of the wet sample (g); $M_{105°C}$: Mass obtained after heating to 105°C (g)

$$VM(\%) = \frac{M_1 - M_2}{M_1 - M_0} \times 100 \quad (6)$$

M_0 : Mass of empty crucible (g); M_1 : Mass of crucible with sample before heating (g); M_2 : Mass of crucible with sample after heating (g); VM : Volatile matter content (%)

$$FCC(\%) = 100 - (H + VM + \textit{ash content}) \quad (7)$$

Thermal characterization

The Briquette thermal characterization was carried out using the lower calorific value (LHV) quantified by equation 8.

$$LHV = \frac{80(100 - \textit{ash content}) \times 4{,}18}{1000} \quad (8)$$

LHV: Lower calorific value (MJ/kg)

The bulk density (ρ) was determined by the ratio between the mass of the briquettes and their geometric volume. This property directly influences handling, storage, and energy density.

Briquette combustion testing

To evaluate the thermal performance of the briquettes, 170 g of fuel for both shapes (Parallelepiped and cylindrical) was introduced into a laboratory water-boiling furnace. 1 liter of water was used for both tests. The briquettes were placed in the furnace firebox and ignited with a blowtorch, with an estimated ignition time of 1 minute. A pot of water was then placed on the stove, and the initial water temperature was recorded with a thermocouple. The water temperature was then measured every 10 minutes. The comparative analysis focused on combustion efficiency given by equation 9.

$$Q = mc\Delta T \quad (9)$$

Q : Amount of heat exchanged (J); m : Mass of the body (kg); c : Specific heat capacity ($J.kg^{-1}°C^{-1}$); ΔT : Change in water temperature (°C)

Results and Discussion

Pyrolysis process evaluation

The evolution of pyrolysis temperature over time is shown in Figure 3. The process lasted 10 hours with a final temperature of 390 °C and an average heating rate of 24.6 °C/h. This rate falls within the recommended range for slow pyrolysis (10–50 °C/h), which promotes gradual biomass degradation and better carbon retention (Manyà, 2012).

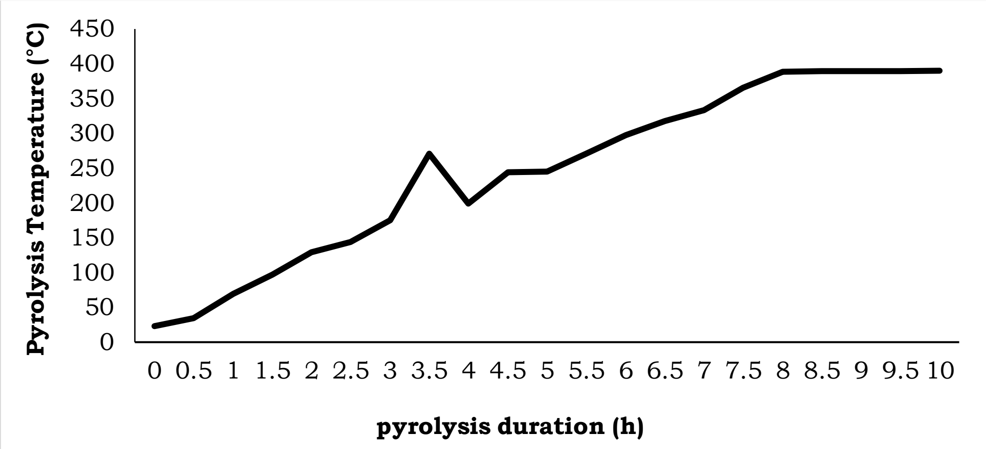


Fig. 3. Evolution of pyrolysis temperature over time.

The temperature readings show an initial moderate increase from 23°C to 129°C during the first two hours, followed by a more rapid rise between 2.5 and 3.5 hours, reaching 270°C. A moderate fluctuation was observed between 3.5 and 5.5 hours, before gradually stabilizing around 390°C between 8 and 10 hours. These variations reflect the heat losses inherent in artisanal kilns, in the absence of fine regulation (Manyà, 2012). The temperature range obtained is consistent with previous studies (Pecchi and Baratieri, 2019). In fact, slow pyrolysis is characterized by a temperature range of 300 to 500°C, yielding solid biochar. It is the same throughout pyrolysis, though the observed time for the temperature rise is slightly higher than in the literature (Lehmann and Joseph, 2015; Alburquerque *et al.*, 2012). The main difference could be related to the pyrolysis reactor performance.

Physical properties

The physical properties of the briquettes are presented in Table 1. A slight difference in bulk density is observed between parallelepiped and cylindrical briquettes, with values of 0.487 g/cm^3 and 0.4738 g/cm^3, respectively.

Table 1. Physical characteristics of briquettes.

Parameters	Parallelepiped briquettes	Cylindrical briquettes
Mass (g)	57.57	53.43
Height (cm)	7.3	7.525
Length (cm)	4.0	
Width (cm)	3.5	
Diameter (cm)		4.3
Volume (cm^3)	118.74	112.81

This difference can be attributed to the shape of the molds used. In fact, the right angles of the parallelepiped molds promote better distribution of the mixture and more uniform compression during manual pressing, thus limiting the formation of internal voids. This results in a slightly higher density and better mechanical cohesion, as noted by Oladeji (2010), who reports that flat-walled molds tend to produce briquettes with greater mechanical strength than rounded molds.

Chemical properties

The chemical properties of the briquettes are presented in Table 2.

Table 2. Chemical characteristics of briquettes.

Parameters	Parallelepiped briquettes	Cylindrical briquettes
Apparent density (g/ cm^3)	0,487	0,4738
Humidity (%)	5	5
Ash content (%)	41,8	41,8
Taux de carbone fixe (%)	52,62	52,62
Volatile matter content (%)	0,58	0,58
LVH (MJ/kg)	19,48	19,48

Chemical parameters such as moisture content (5%), ash (41.8%), fixed carbon (52.62%), volatile matter (0.58%), and lower heating value (19.48 MJ/kg) are identical for both briquette types. This uniformity can be explained by the use of the same raw material (digestate), but this result also shows a homogeneous slow pyrolysis process.

Combustion temperature evaluation

Figure 4 below illustrates the variation in water temperature over time for both briquette types. Regardless of briquette shape, combustion temperatures ranged from 19°C to 62°C at 80 minutes.

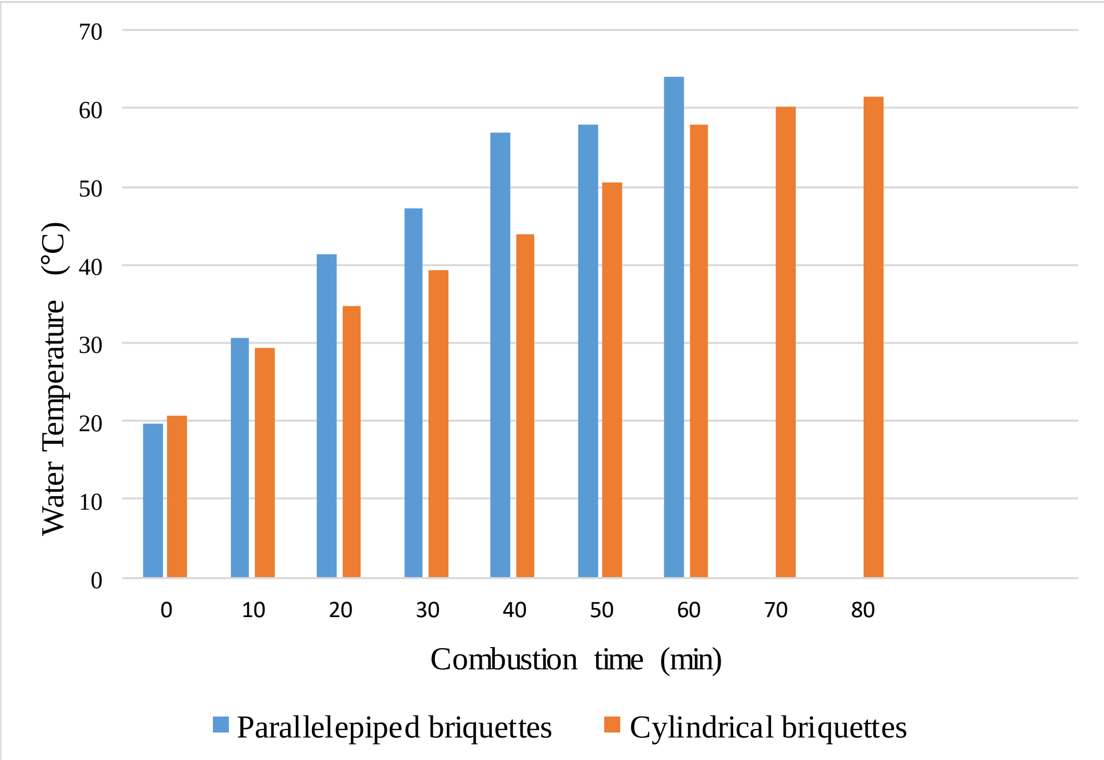


Fig. 4. Evolution of combustion temperature over time for different briquette shapes.

Parallelepiped briquettes achieved the highest combustion temperatures, reaching a maximum of 64°C at 60 minutes, whereas cylindrical briquettes burned much longer, reaching a maximum temperature of 61.6°C at 80 minutes. These results show that the parallelepiped shape promotes a faster rise in temperature, making it suitable for applications requiring immediate heating, while the cylindrical shape maintains a stable temperature for longer.

Briquettes mass evolution during combustion

Table 3 below shows the briquettes' initial and final masses before and after combustion, respectively.

Table 3. Mass variation for different briquettes during combustion.

Briquettes Shape	Duration (min)	Initial mass (g)	Final mass (g)
parallelepiped	60	170	74
Cylindrical	80	170	67

The loss of mass is greater for parallelepiped briquettes (96 g) than for cylindrical briquettes (103 g), reflecting faster, more concentrated combustion in the former and slower but more complete combustion in the latter (Lange *et al.*, 2018).

Water mass diminution during combustion

Table 4 below shows the initial and final water masses before and after combustion, respectively.

Table 4. Water mass variation for different briquettes used as fuel.

Briquettes Shape	Duration (min)	Initial mass (g)	Final mass (g)
parallelepiped	60	1078	1050
Cylindrical	80	1078	996

Water loss is greater for cylindrical briquettes (82 g) than for parallelepiped briquettes (28 g), a direct consequence of their longer burning time (80 min vs. 60 min). These differences are related to the physical properties induced by the geometry of the briquettes. Parallelepipeds have a higher density (0.487 g/cm^3), resulting from stronger compaction, which reduces porosity and limits oxygen circulation (Kaliyan and Morey, 2009). This high density explains their intense, rapid combustion, which releases 0.199 MJ of energy over a shorter period, with limited evaporation.

Conclusion

This study showed that it is possible to recover digestates from the anaerobic co-digestion of cow manure and Tithonia diversifolia into biochar briquettes that meet domestic energy needs, using a traditional process combining solar drying and slow pyrolysis. The results obtained (calorific value: 19.48 MJ/kg, ash: 41.8%, fixed carbon: 52.62%) indicate acceptable energy performance, with a marked influence of geometric shape: parallelepiped briquettes promote rapid temperature rise and are suitable for instantaneous use, while cylindrical briquettes ensure slower, more prolonged combustion. These results highlight the importance of controlling density, moisture content, and compaction to improve thermal efficiency, while providing a sustainable alternative to fossil fuels and reducing deforestation. Future work should explore optimizing production conditions and conducting a socio-economic evaluation of this technology to promote its large-scale adoption.

Acknowledgement

Special thanks to all members of the Rural Engineering Department, especially the workshop at the University of Dschang, in collaboration with the Renewable Energies Laboratory of the University of Dschang.

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