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Research Article

Experimental Investigation of Cocoa Pod Biomass Carbonization: A Pathway to Sustainable Energy

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Abstract: This study evaluates the valorization potential of cocoa pods, mainly sourced from the Sud-Comoé region of Côte d'Ivoire, through controlled thermal pyrolysis to produce biochar. Two experiments were conducted at final temperatures of 331.29 °C and 357.92 °C, yielding biochars with distinct characteristics. The first trial, with a 55% mass yield, produced a biochar with a Lower Heating Value (LHV) of 14.097 MJ/kg, making it suitable for agronomic applications. The second trial, although yielding only 35%, resulted in a higher-energy biochar with a LHV of 22.158 MJ/kg, positioning it closer to high-performance biomasses such as coconut husks (28-32 MJ/kg) and sawdust (18-22 MJ/kg). Processing one ton of cocoa pods is estimated to yield between 350 and 550 kg of biochar, potentially sequestering between 770 kg and 963 kg of CO_2. Compared to direct combustion, this approach avoids approximately 1,063 kg of CO_2 emissions per ton of biomass processed. Thermodynamic modeling using the Hirn cycle estimated the energy potential between 3.662 and 5.815 kWh per ton, depending on yield and LHV. These findings highlight the effectiveness of moderate-temperature pyrolysis in producing energy-rich biochar and reinforce the potential for sustainable valorization of cocoa pod residues within Côte d'Ivoire's agro-environmental development framework.

***Keywords*:** cocoa pods, pyrolysis biochar, energy transition, CO_2 sequestration, sustainable biomass

Abbreviations

m_f	Mass of fuel used (in kg)
LHV	Lower Heating value (in MJ/kg)
W	Electrical energy produced (in MJ or kWh)
η Hirn	Thermal efficiency of the Hirn cycle
E	Available thermal energy
W	Energy conversion
R_m	Mass yield of biomass used
R_m^1	Mass yield of biomass used in experiment 1
R_m^2	Mass yield of biomass used in experiment 2

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T	Temperature measured during pyrolysis
σ	Standard deviation (represents the spread of values)
n	Number of observations
$\bar{x}$	Arithmetic mean of measured values
x_i	Individual measured value
$m_{initial}$ et m_{day}	Initial mass before drying (in g) and Mass after drying (in g)
T_{cl}-T_{c9}	Thermocouples 1 to 9 (temperature sensors placed in the reactor)

1. Introduction

The transition to sustainable energy systems increasingly relies on the local valorization of agricultural residues. In Côte d'Ivoire, the world's leading cocoa producer, post-harvest processing generates large volumes of cocoa pods (*Theobroma cacao* L.), which are generally abandoned or burned in the open air, contributing to soil degradation and greenhouse gas emissions.[1,2]

These residues have a high moisture content (60% to 75%) and are composed mainly of cellulose, hemicellulose, and lignin, making them suitable for thermochemical conversion processes such as slow pyrolysis.[1,3] Adapted to rural areas, this process transforms biomass into three products: biochar, pyrolysis gas, and bio-oil. Biochar, a stable carbonaceous residue, can be used as a solid fuel, an agricultural amendment, or adsorbent material, depending on its physicochemical characteristics.[3,4]

Previous studies have largely focused on high-temperature pyrolysis (≥ 400 °C), which promotes good calorific value but considerably reduces mass yield while requiring high energy consumption.[5] However, recent work in Côte d'Ivoire and elsewhere has shown that moderate temperatures (between 300 °C and 360 °C) produce good-quality biochar with higher yields while reducing energy requirements.[2,6,7]

In particular, Gopal et al. have demonstrated that biochar from cocoa pods pyrolyzed at medium temperatures contributes not only to energy production but also to soil fertility, thanks to its potassium richness and ability to improve water retention.[6,8] Moreover, these circular approaches are part of sustainable agricultural dynamics already underway in several producing regions.[4,9] This study draws on the principles of thermochemical biomass transformation to assess the performance of slow pyrolysis at moderate temperatures.

Theoretically, the study is based on the principles of thermochemical transformation of biomass, and performance assessment is based on two key parameters:

(1) mass yield, expressed as % of biochar produced,

(2) energy quality, measured in terms of Lower Heating Value (LHV).

A Quality-Quantity Compromise (QQC) index is proposed to synthesize these two aspects. The experiment was carried out on cocoa pods collected in the south of Côte d'Ivoire, dried and subjected to two pyrolysis conditions. The present study uses an integrated experimental and thermodynamic approach to explore the impact of moderate temperatures (331.29 °C and 357.92 °C) on the performance of biochar derived from cocoa pods. It stands out for obtaining a high LHV (22.158 MJ/kg) at only 357.92 °C, which represents an advance on the thresholds generally required in the literature. This result suggests the possibility of energy optimization at lower cost, with concrete implications for local agricultural practices. In addition, an estimate of the recoverable electrical potential is proposed to envisage scenarios for integrating biochar into decentralized energy systems. This dual experimental and applicative approach aims to reinforce the viability of small-scale pyrolysis as a sustainable management solution for agricultural residues in Côte d'Ivoire.

2. Materials and methods

2.1 *Materials*

2.1.1 *Biomass used*

The cocoa pods (Figure 1) used in this study came from agricultural cooperatives in Aboisso (Sud-Comoé, Côte d'Ivoire). After drying to below 10% moisture, the biomass was kept dry to ensure uniform pyrolysis. The moisture content of the cocoa pod husks was evaluated using the standard gravimetric method, in accordance with the ISO 18134-1:2015, the standard on the determination of moisture in solid biofuels. Specifically, a representative biomass sample (approximately 10 g) was precisely weighed and placed in a ventilated oven at 105 °C ± 2 °C for 24 h until the mass stabilized. Moisture content was calculated using the following formula:

$$\text{Moisture}(\%) = \frac{m_{\text{initial}} - m_{\text{dry}}}{m_{\text{initial}}} \times 100 \tag{1}$$

All measurements were carried out in triplicate to ensure the reliability of the results.

Figure 1. Preparation of cocoa pods

2.1.2 *Reactor and pyrolysis conditions*

The reactor used was a controlled pyrolysis furnace, built from a recycled metal barrel and equipped with nine *K*-type thermocouples placed at strategic points to ensure precise monitoring of internal temperatures during the process. Two experimental trials were conducted, each starting at 113.65 °C and ending respectively at 331.29 °C and at 357.92 °C. After pyrolysis, the biochar was allowed to cool inside the reactor for two hours before being exposed to ambient air. Figure 2a shows the biomass pyrolysis reactor, which is housed inside the complete experimental system. Figure 2b illustrates the full setup, including the reactor, thermocouple wiring, data acquisition system, and monitoring computer used to record the thermal evolution during the tests.

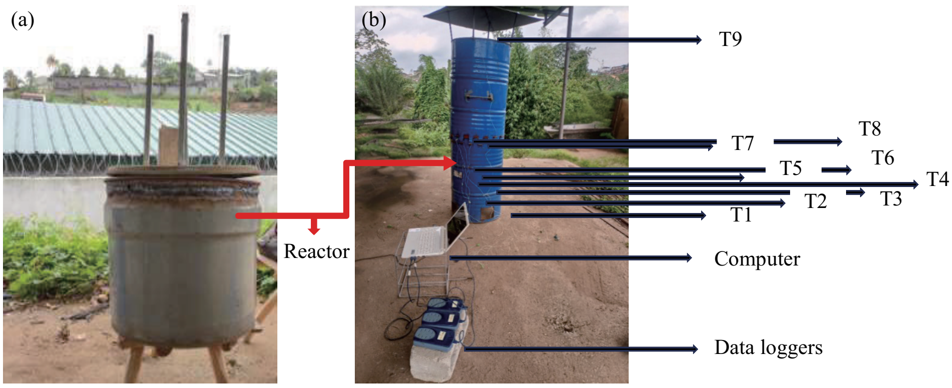

Figure 2. (a) View of the pyrolysis reactor containing biomass, constructed from a recycled metal barrel, (b) Full schematic of the pyrolysis reactor showing the placement of nine *K*-type thermocouples (T1-T9) for accurate temperature tracking during the experiment

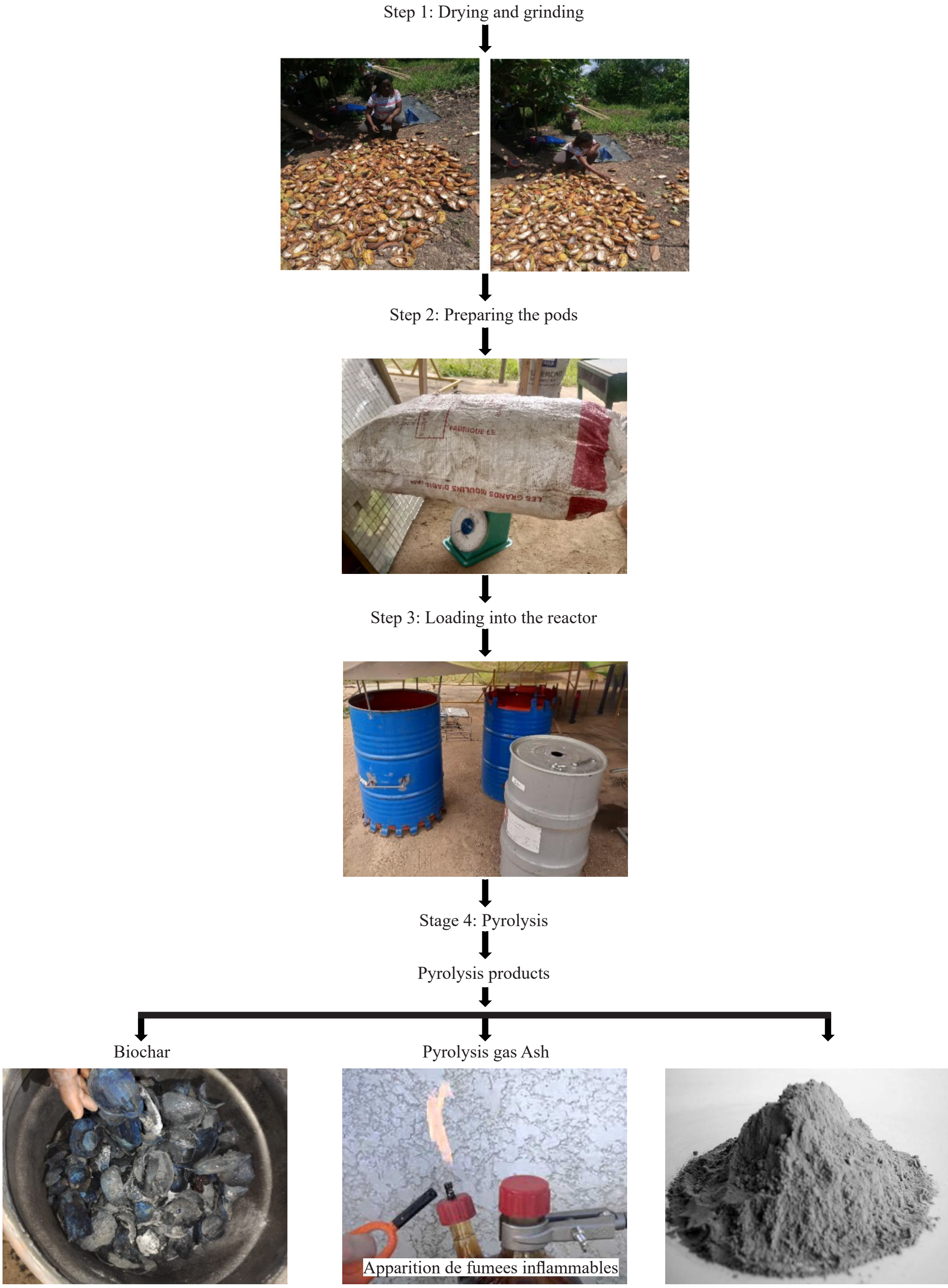

Figure 3. Stages in the carbonization process

2.2 *Methods*

This research, carried out as part of a Master's study explores the valorization of cocoa pods by thermal pyrolysis. In Figure 3 shows the various stages of carbonization process. Experiments conducted at different temperatures analyzes the impact of pyrolysis conditions on the biochar's mass yield and energy performance.

2.2.1 *Measurements of temperature*

To accurately monitor temperature variations during pyrolysis, a system of nine (9) *K*-type thermocouples (chromel-alumel, up to 1,350 °C) was installed and connected to a computer (Figure 2b). Each sensor was positioned at a strategic point in the furnace: T1 at the bottom of the kiln, near the pods; T2 in the middle zone, between T1 and T3; T3 near the kiln exit; T4 on the side of the combustion chamber; T5 near the external evacuation zone; T6 at the entrance to the pyrolysis zone; T7 in the middle of it; T8 towards secondary combustion; and T9 outside for ambient control.

The device enabled automatic recording as soon as the fuel was introduced, with a chronometer triggered to monitor the duration of the process. Two pyrolysis cycles were carried out: the first between 11:00 and 12:42 at 331.29 °C, the second from 14:42 to 17:51 reaching 357.92 °C. Under the effect of this high heat, five of the nine thermocouples were destroyed, with only T1 to T4 providing reliable data throughout the experiment (Figure 4). This system enabled rigorous monitoring of the thermal profile, guaranteeing the validity of the measurements and the quality of the biochar obtained.

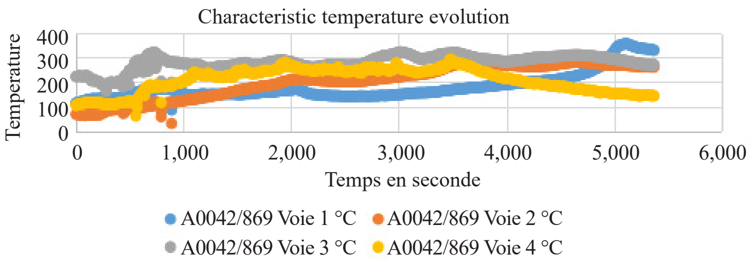

Figure 4. Characteristic temperature evolution curves as a function of time

2.2.2 *Characterization of the biochar obtained*

The biochar parameters analyzed include: moisture content, ash content, Hydrogen (H), Sulfur (S), and Lower Heating Value (LHV). All these measurements were carried out at the Central Analysis Laboratory of the Polytechnic University of Man, using a calorimetric bomb. The analysis was conducted under the operating settings listed in Table 1 below.

Table 1. Operating settings of the calorimetric bomb used for the measurements

Voltage	50	kV
Filter	Mid	
Meas time	60	s
Current	178	μA
Collimator	7 mm	
Processing time	Process 2	

The LHV of biochar is inversely correlated with the mass yield (R_m) obtained during pyrolysis. In general, a higher yield (i.e., more biochar produced) corresponds to a lower LHV, due to the retention of more volatile matter and less complete carbonization. Conversely, higher pyrolysis temperatures promote devolatilization, resulting in increased LHV but reduced mass yield, thereby illustrating the typical trade-off between biochar quantity and energy quality. This inverse relationship has been confirmed by several studies, which also highlight the influence of biomass particle size and thermal regime on both yield and calorific value.[10,11]

The LHV of the second experiment was obtained experimentally, while that of the first experiment could not be measured directly. To estimate the LHV of the first experiment, a proportional relationship is used based on the mass yields (R_m) of the two experiments: hence this relationship:

$$\text{LHV1} = \text{LHV2} \times \frac{R_m^2}{R_m^1} \tag{2}$$

However, it is essential to note that these estimates may include a certain margin of error, and direct calorimetric analyses would be necessary to obtain accurate values.

2.2.3 *Thermodynamic analysis*

The Hirn cycle has been modeled to assess the energy conversion potential of biochar derived from cocoa pods. This approach enables the estimation of available thermal energy (E) and its conversion into electrical energy (W) based on the thermal efficiency (η) of the cycle, typically ranging between 30% and 40%. A study by Milkov et al. demonstrated the application of the Rankine-Hirn cycle for heat recovery in diesel engine exhaust systems, illustrating its potential for energy conversion in agricultural contexts.[12]

The available thermal energy (E) is calculated by multiplying the mass of biochar produced by the

$$E = m_f \times \text{LHV} \tag{3}$$

It is important to note that the calculation of available thermal energy using the formula $E = m_f \times \text{LHV}$ represents a theoretical maximum estimate and does not assume 100% energy conversion efficiency. This value is intended to assess the energy potential stored in the biochar, regardless of thermal losses or system limitations. It serves as a reference for comparing the energy performance of different biomass types or experimental conditions.

Then use this formula to find the electrical energy:

$$W = \eta\text{Hirn} \times E \tag{4}$$

2.2.4 *Environmental impact*

The CO_2 emissions avoided by pyrolysis are calculated by comparing the direct combustion of pods with their transformation into biochar. The formula used is:

$$CO_2 \text{ emis (kg)} = \text{mass of carbon trapped or burned (kg)} \times \frac{\text{Molar Mass of } CO_2 (44)}{\text{Molar Mass of C}(12)} \tag{5}$$

This approach makes it possible to quantify the environmental benefits of converting cocoa pods into biochar.

Precise calculations and detailed numerical values, such as yields, LHV, and CO_2 emissions, will be presented in the "Results" section as tables or numerical applications to facilitate their interpretation and comparison.

3. Results and discussion

3.1 *Experimental results*

Table 2 shows the main changes in cocoa pods after pyrolysis. The moisture content drops from 10.2% to 2.5%, and volatile matter is significantly reduced, while fixed carbon increases from 16.7% to 72.1%. The ash content is multiplied by a factor of five, and the Lower Heating Value (LHV) increases markedly, reaching 22.16 MJ/kg. This confirms the effectiveness of pyrolysis for producing an energy-rich solid fuel. Additionally, phosphorus content more than doubles, highlighting the biochar's potential as a nutrient-rich soil amendment.

Table 2. Proximate analysis of raw cocoa pods and their derived biochar (% dry weight)

Parameter	Raw cocoa pods	Biochar	Source/Notes
Moisture	10.2%	2.5%	Estimated for raw pods;[1] measured or typical for biochar[2]
Volatile matter	68.4%	21.7%	Typical values from cocoa biomass and slow pyrolysis biochar[2,3]
Fixed carbon	16.7%	72.1%	Calculated by difference (100-moisture-volatiles-ash)
Ash content	4.7%	23.7%	From literature for raw pods;[1] measured in Excel data for biochar
Lower Heating Value (LHV)	11.6 MJ/kg	22.16 MJ/kg	Estimated for raw pods;[1] measured for biochar
Phosphorus (P) content	0.45%	1.21%	Average from West African data;[1] measured in Excel (12.062 ppm)

Table 3. Temperatures recorded on channels 1 to 4 for the first experience

Time taken (s)	1	5,374
Selected routes (°C)	Start	End
Track 1	113.65	331.29 for the first experience
Track 2	68.49	263.46
Track 3	223.49	271.36
Track 4	105.28	143.13

Table 4. Temperatures recorded on channels 1 to 4 for the second experience

Time taken (s)	1	5,374
Selected routes (°C)	Start	End
Track 1	113.65	357.92 for the second experience
Track 2	76.34	279.42
Track 3	218.41	283.46
Track 4	112.17	134.23

During the pyrolysis experiment in Table 3 and Table 4, nine *K*-type thermocouples were installed at various points in the furnace. However, only four of them (T1 to T4) provided usable data for the entire process. These sensors were located respectively at the bottom of the furnace, in the center, near the outlet, and on the combustion side.

Two pyrolyses were carried out:

- The first, between 11:00 and 12:42, reached 331.29 °C;
- The second, longer pyrolysis, between 14:42 and 17:51, reached 357.92 °C.

These measurements made it possible to effectively monitor thermal evolution and relate the temperatures reached to the energy performance of the biochar obtained.

The mass yield (R_m) measures the proportion of biochar recovered relative to the initial mass of biomass. The general formula for its calculation is

$$R_m = \frac{\text{Mass of biochar produced (kg)}}{\text{Initial mass of biochar (kg)}} \times 100 \tag{6}$$

This study evaluated the yields for two experiments, each calculated from the measured masses. Proportion of biochar recovered relative to initial mass. (For 4.9 kg of empty cocoa pods, 2.7 for experiment 1 at 1 h 42 min and 1.7 kg for experiment 2 at 3 hours and 9 minutes) of biochar was obtained.

First experience: R_m = 55%.

Second experiment: R_m = 34.69% environ 35%.

$$\text{QQC} = R_m \times \text{LHV} \tag{7}$$

The Quality-Quantity Compromise (QQC) score obtained for the second experiment (357.92 °C) was 777.0 MJ, slightly higher than that of the first experiment (331.29 °C), which reached 775.5 MJ. This indicates that the higher temperature pyrolysis provides a more favorable overall compromise between the amount of biochar produced and its energy quality, despite a lower mass yield.

Table 5. The pyrolysis experiment results

Parameter	Experiment 1 (331.29 °C)	Experiment 2 (357.92 °C)
Mass of biochar (kg)	2.70 ± 0.02	1.70 ± 0.02
Mass yield (%)	55.10 ± 0.41	34.69 ± 0.41
Calorific value (MJ/kg)	14.07 ± 0.15	22.17 ± 0.25

These results in Table 5 show a higher yield at lower temperatures, but a higher calorific value at higher temperatures, illustrating the classic compromise observed in slow pyrolysis processes. The biochar obtained at 331.29 °C is therefore more interesting for high-yield applications, while that at 357.92 °C has a better energy density.

The sample image of biochar obtained at 357.92 °C was shown in Figure 5, and key parameters measured by calorimetry were listed in Table 6.

Table 6. Key parameters of biochar measured by calorimetry

Elements	Humidity level	Hydrogen rate	Souffre rate	Ash rate	Lower Heating Value (LHV)
Value in % by mass	9.25	5.5	8.25	23.43	22.158 MJ/kg

Figure 5. Sample image of biochar obtained at 357.92 °C

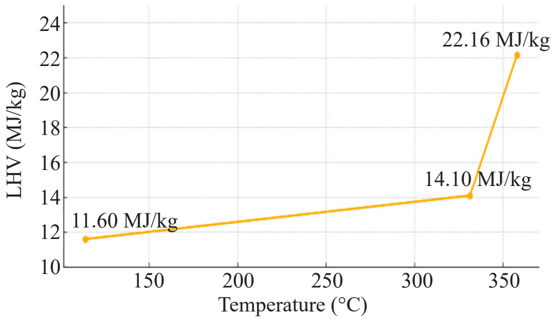

Figure 6. Lower Heating Value (LHV) of cocoa pod biochar vs pyrolysis temperature

3.2 *Modeling the Hirn cycle to estimate energy conversion potential*

The small difference in total thermal energy (38,062.2 MJ vs. 37,668.6 MJ) in Table 7 is explained by a compensation effect between the mass of biochar produced and its Lower Heating Value (LHV) (Figure 6).

The first experiment has a higher mass yield, but a lower LHV. The second produces less biochar, but with a higher LHV. The product of these two variables (mass × LHV) results in a similar final thermal energy.

Table 7. Experimental results: comparison of energy parameters

Parameter	First experience	Second experiment
Mass of biochar produced (kg)	550	350
Mass yield (R_m_f)	55%	35%
LHV (MJ/kg)	14,097	22,158
Available thermal energy (MJ)	38,062.2	37,668.6
Potential electrical energy (MJ)	20,934.21	13,184.01
Electrical energy (kWh)	5,815.06	3,662

This compromise is typical of pyrolysis processes: the higher the temperature, the more the material is carbonized, which reduces the quantity but increases the energy quality of the biochar.

As the data do not allow us to estimate fixed carbon precisely, The calculation of estimated CO_2 emissions avoided compared to the use of fossil fuels is based on typical values for biochars produced by pyrolysis.

Fixed carbon content of biochars generally ranges between 50% and 80%, depending on pyrolysis temperature.[13]

Our pyrolysis is carried out at approximately 350 °C, and a fixed carbon content of around 60-65% is often used as a reasonable assumption.[14]

If cocoa pods are burned directly, they contain around 50% carbon on average. The CO_2 emissions for 1 tonne of pods are then: CO_2 emission (kg) ≈ 1,833 kg.

Table 8 below shows the main results obtained for the two pyrolysis experiments, as well as a direct combustion scenario used as a point of comparison. It allows us to observe the variations between the approaches in terms of mass yield, carbon trapped or emitted, and associated emissions (CO_2 and SO_2).

SO_2 emissions generated by the complete combustion of biochar are influenced by sulfur content. In this study:

- First experiment: 550 kg of biochar containing 8.25% sulfur emits around 181.5 kg SO_2 per tonne of pods.
- Second experiment: 346.9 kg of biochar with 8.25% sulfur emits around 165 kg of SO_2 per tonne.

Table 8. Comparative results: Emissions of CO_2 and SO_2

Parameter	First experience (biochar)	Second experiment (biochar)	Direct combustion
Mass yield (R_m)	55%	35%	-
Mass of biochar or carbon (kg)	550	350	500
Mass of carbon trapped or burned (kg)	330	210	500
CO_2 emissions (kg)	1,210	770	1,833
Net CO_2 reduction (kg)	623	1,063	-
SO_2 emissions (kg)	181.5	165	-

3.3 *Discussions*

Two trials were carried out on 4.9 kg of empty cocoa pods using a controlled pyrolysis protocol. The first trial, lasting 1 h 42 min, reached a final temperature of 331.29 °C and yielded 2.7 kg of biochar, representing a mass yield of 55%. The second trial, lasting 3 h 9 min, reached a final temperature of 357.92 °C, with a recovered biochar mass of 1.7 kg, representing a yield of 35%.

Although the two trials were designed as replicates, the variation in final temperature and residence time led to two distinct experimental conditions. The results reveal a classic trade-off in thermal pyrolysis processes: a lower temperature (331.29 °C) favors better material recovery, while a higher temperature (357.92 °C) significantly improves the energy quality of the biochar. The LHV rises from 14.097 MJ/kg to 22.158 MJ/kg.

In comparison with other works, the pyrolysis temperatures used here remain relatively low. For instance, recent research by Diallo et al. showed that cocoa pods treated at 300-400 °C yield an LHV of 16.5-17.8 MJ/kg,[16] while Koné et al. reported a value close to 19 MJ/kg at 350 °C.[17] Kwarteng et al. recorded an LHV of 25 MJ/kg at 500 °C with approximately 22% ash content.[18] These results confirm that a pyrolysis temperature around 357.92 °C offers a good compromise between yield and energy content.

Thermodynamic analysis based on the Hirn cycle enabled us to estimate the usable energy potential of biochar. At 357.92 °C (LHV = 22.158 MJ/kg), 1.7 kg of biochar can produce 37.668 MJ of heat, or 3.662 kWh of electricity at a thermal efficiency of 35%. At 331.29°C (LHV = 14.097 MJ/kg), 2.7 kg of biochar generates 38.062 MJ of heat, equivalent to 5.815 kWh of electricity.

The biochar analyzed has an ash content of 23.43%, which is higher than that of many commonly used biomasses. For instance, coconut husks typically contain less than 10% ash,[19] while sawdust contains around 15%.[20] Despite this high ash content, cocoa pod biochar remains relevant for agronomic uses due to its high potassium and calcium concentrations.

Table 9. Comparison of the LHV of cocoa pod biochar with other biomasses

References	Biomass	Pyrolysis temperature (°C)	LHV (MJ/kg)	Ash content (%)	CO_2 avoided (kg/ton)
Christelle OGO[15]	Cocoa pods	357.92	22.158	23.43	~ 1,063
Diallo et al.[16]	Cocoa pods	300-400	16.5-17.8	~ 20	Not rated
Koné et al.[17]	Cocoa pods	350	~ 19.0	~ 18	Not rated
Kwarteng et al.[18]	Cocoa pods	500	25.0	~ 22	~ 1,200
Zhang et al.[19]	Coconut husks	-	28.0-32.0	< 10	~ 1,380
Smith et al.[20]	Sawdust	-	18.0-22.0	~ 15	~ 720

These results in Table 9 confirm that cocoa pod biochar is competitive in terms of calorific value, with additional benefits for carbon sequestration and soil enrichment. However, the high ash content remains a constraint for high-efficiency industrial energy applications.

The standard deviations (± 0.02 kg for mass, ± 0.41% for yield, ± 0.15-0.25 MJ/kg for LHV) were relatively low, indicating high reproducibility. This reinforces the reliability of the thermal measurement system based on nine *K*-type thermocouples, four of which delivered usable data throughout the experiments.

It is important to stress that this study is based on just two trials. Due to the absence of experimental replicates for each condition, no rigorous statistical analysis can be carried out. The results presented must therefore be considered preliminary. They do, however, provide a sound basis for formulating hypotheses and guiding future research. It is recommended that further trials be carried out with several replicates in order to validate the observed trends and optimize pyrolysis parameters according to the targeted energy or agricultural uses.

SO_2 emissions can be reduced via desulfurization processes or by directing biochar towards non-energy applications (e.g., agriculture), particularly in uses requiring a low environmental footprint.

Pyrolysis of cocoa pods also offers notable environmental benefits. Per tonne of pods, around 770 kg of CO_2 is sequestered, compared with 1,833 kg of CO_2 emitted during direct combustion, thus avoiding 1,063 kg of CO_2.[21] Pods have good emission reduction potential and significant local abundance compared to other biomasses, particularly in Côte d'Ivoire.[22]

These results confirm that optimizing pyrolysis temperatures is essential to align biochar production with energy or agricultural objectives. Moreover, converting pods into biochar is a sustainable solution for reducing greenhouse gas emissions, promoting the energy transition, and valorizing agricultural residues.[23]

4. Conclusion

Experiments have shown that pyrolysis of cocoa pods is a promising way of recovering agricultural residues. Mass yields of 55% and 35%, as well as Lower Heating Values (LHV) of 14.097 MJ/kg and 22.158 MJ/kg obtained, offer flexibility depending on the applications envisaged, whether to maximize the quantity of biochar or its energy density. The estimated carbon balance of 1,063 kg of CO_2 avoided per tonne of biochar produced reinforces the environmental interest of this approach.

However, this study is based on two trials carried out under slightly different final temperature conditions. Although these results provide relevant insights into the effect of temperature on biochar characteristics, the lack of experimental replicates limits the statistical significance of the conclusions. These results should therefore be regarded as preliminary. Further trials are required to statistically validate the trends observed.

Nevertheless, these results highlight optimization strategies, in particular raising the pyrolysis temperature above 357.92 °C to improve the LHV while maintaining a good mass yield.[18,21] The integration of biochar into local energy networks, combined with a comprehensive life-cycle analysis, is an essential approach to fully harness its energy potential and minimize its environmental impacts.

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Conflict of interest

The authors declare that they have no financial, commercial, or personal conflicts of interest regarding the work presented in this article. The study was conducted independently, without third-party influence, and the results obtained strictly reflect the experimental data and analyses performed.

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