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Research Article

Towards Electricity from the Combustion of Agricultural Waste in Boilers with Low CO_2 Emissions

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Abstract: To meet the growing energy needs of the world's population, international governments have turned to biomass energy from agricultural waste as a form of renewable energy. To this end, this study is based on the experimental and practical determination of certain physicochemical properties of three agricultural residues (cocoa cortex, oil palm fibres and sugar cane bagasse) using approximate and structural analysis methods. Then, using a METERK electronic detector, the small quantities of CO_2 emitted during combustion in 0.5 g boilers of each of these waste products used to produce energy (heat and/or electricity) were determined. The gross and net calorific values of these biomasses were also determined. Here are some of the results obtained for these three agricultural residues: variable moisture content (from 3.6% to 43.12%), variable organic matter content (from 76.12% to 90.31%), cellulose content (from 32.74% to 55.91%), lignin content (from 8.26% to 27.05%), variable net calorific values (from 6.581 kWh/kg to 10.461 kWh/kg) and low CO_2 gas emissions (from 439 ppm to 447 ppm). This proves that these three agricultural residues are very good potential sources of energy that can be used as fuel in boilers to produce large quantities of heat that can be converted into electricity by turbines connected to alternators using electromagnetic induction phenomena. Finally, this work provides credible information for public and private decision-makers in the field of electricity production from the combustion of these agricultural residues in boilers.

***Keywords*:** biomass, agricultural residues, combustion, boilers, energy, gross calorific values, net calorific values, ash and CO_2 gaseous emissions

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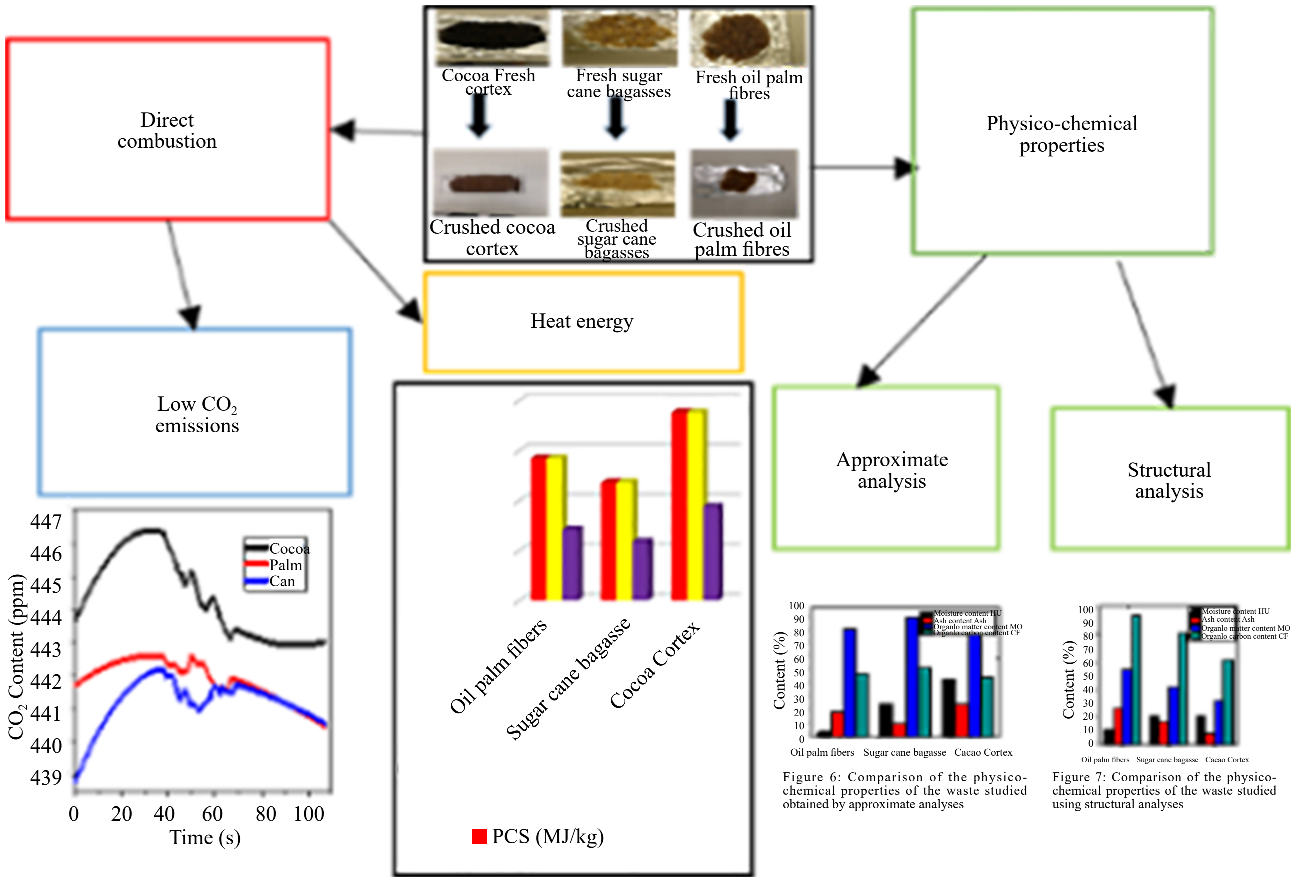
Graphical abstract



1. Introduction

The world's energy needs linked to population growth are driving industrial growth, sometimes despite the environmental impact of greenhouse gas emissions.[1] The depletion of fossil energy resources, followed by environmental constraints due to the emission of greenhouse gases and atmospheric pollutants, has led to the implementation of global energy strategies and policies aimed at optimising the production and consumption of renewable, clean or healthy energy sources.[2] There are several types of renewable energy, such as wind power (onshore and offshore), solar energy (photovoltaic, thermal and thermodynamic), hydropower, geothermal energy and biomass energy.[3] Among these renewable energies, our study focused on the energy produced by biomass. Biomass occupies a very important place in the world's energy potential by 2050. It could supply around 25% of the world's energy needs.[4] In energy terms, biomass represents all biodegradable renewable organic matter of plant or animal origin that can become a source of energy via three main conversion routes: physical, thermochemical and biochemical.[5] In physical conversion processes, biomass is transformed into a solid fuel by densification methods (grinding, sieving, drying and pelletising).[6] In thermochemical conversion processes, heat and chemical catalysts are used to transform biomass into high-energy products (heat, bio-oil, bio-char and gas).[7] In biochemical processes, enzymes and micro-organisms are used to transform biomass into energy products (bioethanol and biogas).[8] Of all these processes for recovering energy from biomass, this work is based specifically on the method of direct combustion of three agricultural residues (cocoa cortex, oil palm fibres and sugar cane bagasse) in boilers to produce heat that can be converted into electricity by turbines using electromagnetic induction phenomena. These agricultural residues mainly contain carbon C, hydrogen H, oxygen O and small quantities of atoms (nitrogen N and sulphur S).[9] The combustion of agricultural waste biomass to produce energy (heat) can be represented by the following general equation (1) taken from.[10]

$$C_aH_bO_cN_dS_d+\left(a+\frac{b}{2}+e-c\right)(1+x)(O_2+3.8N_2)\rightarrow aCO_2+bH_2O+\left(a+\frac{b}{2}+e-c\right)(1+x)(3.76+d)N_2$$

$$+\left(a+\frac{b}{2}+e-c\right)O_2+eSO_2 \qquad (1)$$

The agricultural waste was collected from plantations, restaurants and homes in Côte d'Ivoire. This study determined the actual quantities of CO_2 gas emissions[11] released during the combustion of this agricultural waste in a small electric boiler adapted to the laboratory, using an accurate electronic CO_2 gas detector placed at a regulatory distance of at least 1 m from the boiler. To determine certain physicochemical properties of the waste studied, approximate analyses and structural analyses were carried out beforehand. The gross calorific values (PCS) of these biomasses were determined experimentally and their net calorific values (PCI) were deduced.[11] This research will enable the scientific community and the whole world to really know the quantities of energy produced by the combustion of each of these agricultural waste products. At the same time, it will reveal the exact quantities of CO_2 emitted into the atmosphere during this operation. This will provide credible information to decision-makers about the installation of cogeneration units using this agricultural waste as fuel to produce electricity in a healthy environment.

2. Materials, techniques and methods used

2.1 *Agricultural waste studied*

The agricultural wastes studied were cocoa cortex, oil palm fibre and sugar cane bagasse. These agricultural residues were dried and then ground before their physical and chemical properties were determined,[12] see Figure 1 below.

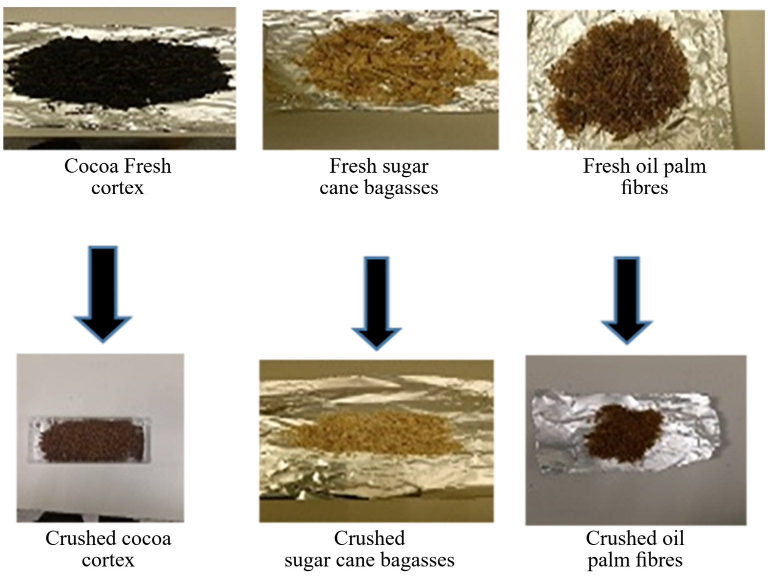


Figure 1. Agricultural waste studied

2.2 *Determination of the physico-chemical properties of the waste studied*

Approximate and structural analysis methods were used to determine the physico-chemical properties of agricultural waste, which is lignocellulosic biomass:[13] moisture content (% Hu), ash content (% Cendres), organic matter or volatile dry matter content (% OM), fixed organic carbon content (% CF), fibre content (F%), hemicellulose content (H%), cellulose content (C%) and lignin content (L%).

2.2.1 *Approximate analyses*

Approximate analyses were carried out to determine: moisture content (% Hu), ash content (% Ash), volatile organic matter or dry matter content (% OM), fixed organic carbon content (% CF).[14]

2.2.1.1 *Moisture content (% Hu)*

The AFNOR NF U 44-171 standardised method of October 1982 consists of steaming a quantity of waste equal to or greater than 100 ± 0.1 g at 105 ± 2 °C for 24 hours until a constant mass is obtained.[15] In this study, 50 g of waste was collected from plantations, restaurants and homes and dried in an oven at 105 °C until a constant mass was obtained (Figure 2). The moisture content (% Hu) is determined by the difference in mass of the sample before and after drying, according to equation (2) below:

$$\%Hu = \frac{(M_0 - M_1)\times 100}{M_0} \tag{2}$$

With:
% Hu: Moisture content.
M_0: initial mass of sample before drying (50 g).
M_1: final mass of the sample after drying at 105 °C.

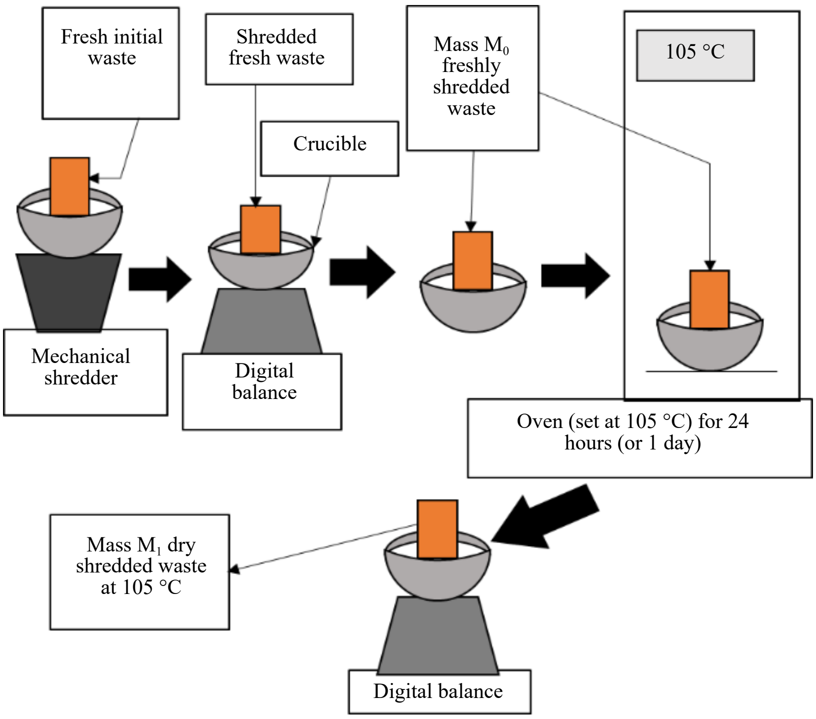


Figure 2. Moisture content diagram (% Hu)

2.2.1.2 *Volatile dry matter (% MSV) or organic matter content (% OM)*

The volatile dry matter content was determined from waste previously placed in an oven at 105 °C at constant mass and calcined at 550 °C for 4 hours using a Nabertherm oven (Figure 3). According to the French standard for the analysis of culture media (AFNOR NF U 44-160, (1985)).[16] The rate of volatile dry matter (% MSV) or organic matter (% OM) is obtained by the following formula (3):

$$\%OM = \frac{(M_1 - M_2) \times 100}{M_1} \quad (3)$$

With:
% OM: Volatile dry matter or organic matter content (% MSV).
M_1: mass of waste at 105 °C.
M_2: mass of waste at 550 °C.

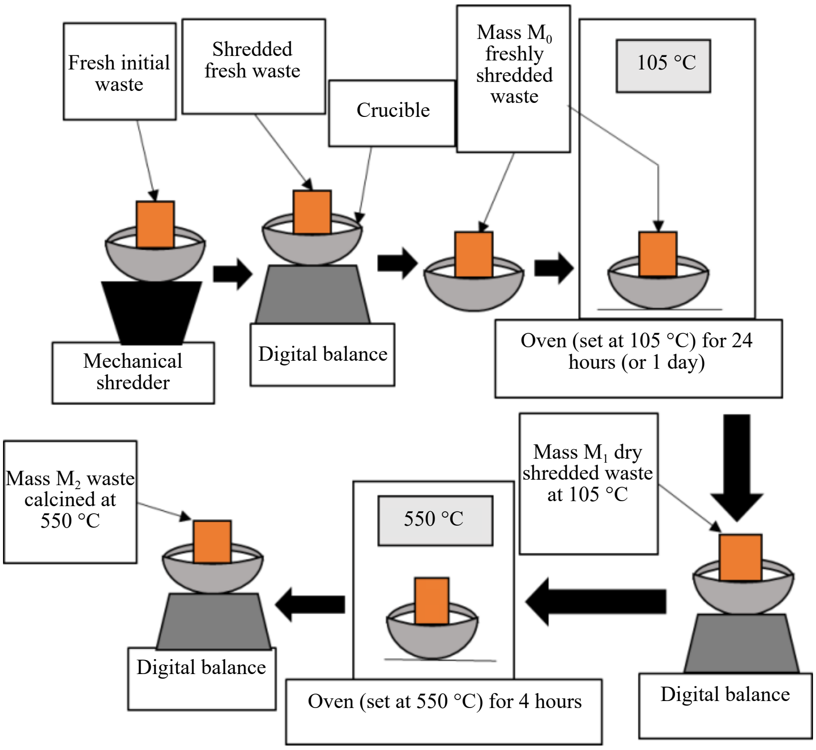


Figure 3. Diagram of organic matter content (% OM)

2.2.1.3 *Ash content (% Ash) or (% MM)*

After obtaining the organic matter or volatile dry matter content, the ash or mineral matter content can be deduced according to equation (4) of:[16]

$$\%MM = \%Ash = 100 - \%OM = 100 - \frac{(M_1 - M_2) \times 100}{M_1} = \frac{M_2 \times 100}{M_1} \quad (4)$$

With:
% OM: Volatile dry matter or organic matter content (% MSV).

M_1: mass of waste at 105 °C.
M_2: mass of waste at 550 °C.

2.2.1.4 *Total organic carbon content (% CF)*

Once the volatile dry matter content (% MSV) has been determined, the fixed organic carbon content (% CF) is deduced according to equation (5) of the French standard for the analysis of culture media (AFNOR NF U 44-160, (1985)).[16]

$$\%CF = \frac{\%MSV}{1.725} = \frac{\%OM}{1.725} \tag{5}$$

With:
% OM: percentage of organic matter or volatile dry matter (% MSV).

2.2.2 *Structural analysis*

The contents of fibre F (%), cellulose C (%), hemicellulose H (%) and lignin L (%) were determined by structural analysis. Analysis of extractable lignin, hemicellulose, cellulose and acid-insoluble lignin was carried out according to the protocol described in.[17,18,19] The analysis must be carried out at least once, with a maximum standard deviation of 5%. Here are the various stages in the protocol adopted. The sample was first crushed, sieved (< 500 µm) and dried at 105 °C for 12 h.

2.2.2.1 *Extractable content soluble in toluene-ethanol Ex (%)*

A 3 g (mL) sample (m_1) was used to extract the extractable. The sample was dispersed in 150 mL of a toluene-ethanol solution (2:1). The mixture was stirred for 3 hours. The residue obtained by Büchner filtration was dried at 105 °C for 2 hours and then weighed (m_2). The mass of extractable corresponds to the mass loss of the sample. The extractable fraction was determined according to the following equation (6):

$$Ex(\%) = \frac{(m_1 - m_2) \times 100}{m_1} \tag{6}$$

The residue obtained is used to determine the acid-insoluble hemicellulose and lignin content.

2.2.2.2 *Hemicellulose H content (%)*

A 1 g sample (m_3) of the residue is dispersed in 150 mL of a NaOH solution (20 g/L). The mixture was placed in a flask and topped up in a reflux system. Boiling lasted 3.5 hours. The solid obtained by Büchner filtration was washed four times with 150 mL of distilled water to remove the Na^+ ions. It was then dried at 105 °C for 24 hours and weighed (m_4). The hemicellulose content H (%) was determined from the loss in mass of the sample after this treatment according to equation (7):

$$H(\%) = \frac{(m_3 - m_4) \times (100 - Ex)}{m_3} \tag{7}$$

2.2.2.3 *Acid-insoluble lignin content L (%)*

A volume of 30 mL of 72% sulphuric acid is poured gently over a mass of approximately 1 g (m_5) of biomass residue from the toluene and ethanol extraction stage. The mixture is kept at a temperature of between 8 °C and 15 °C for 24 hours. A volume of 300 mL of distilled water was then added and the mixture was boiled for 1 hour using a reflux system. The solid obtained was filtered through a Büchner filter, washed on the filter 3 times with 150 mL of distilled water to remove SO_4^{2-} ions, dried at 105 °C for 24 h and weighed (m_6). The lignin content L (%) was determined from the final mass of the solid residue using equation (8) below:

$$L(\%) = \frac{m_6 \times (100 - Ex)}{m_5} \tag{8}$$

2.2.2.4 *Cellulose content C (%)*

The cellulose content C (%) is determined by the difference (9) below:

$$C(\%) = 100 - Ex - H(\%) - L(\%) \tag{9}$$

2.2.2.5 *F-fibre content (%)*

The fibre content F (%) is determined by formula (10) of:[20]

$$F(\%) = H(\%) + C(\%) + L(\%) \tag{10}$$

Figure 4 below shows the diagram used to determine lignin, hemicellulose and cellulose content.

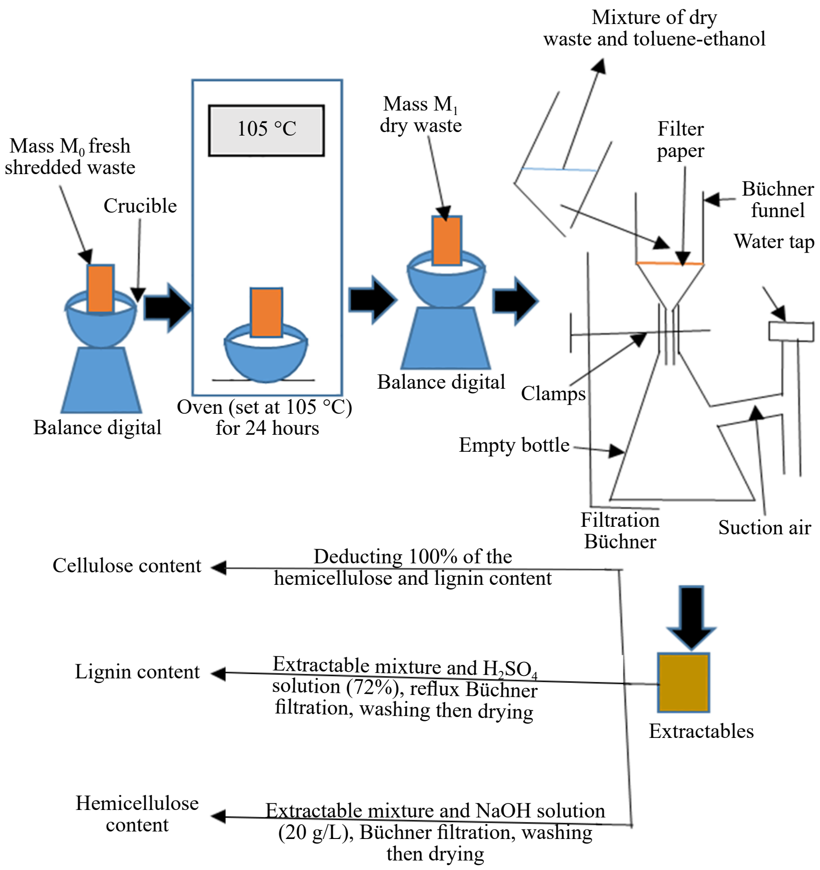


Figure 4. Diagram for determining lignin, hemicellulose and cellulose content

2.3 *Determining the calorific values of the agricultural waste studied*

The calorific value represents the quantity of energy contained in a unit mass of fuel (J/g). A distinction is made between the gross calorific value (PCS) and the net calorific value (PCI). For this study, the analyses were carried out in a bomb calorimeter (type Parr, model 6200), in the presence of oxygen. The apparatus was calibrated using a fuel with a known calorific value, benzoic acid (PC = 26.453 J/g), which made it possible to determine the water equivalent. The gross calorific value is calculated automatically using equation (11) from:[21]

$$m_{comb} \times PCS = (m_e + m_{eqcal}) \times CP\,(T_F - T_O) \tag{11}$$

With:

m_{comb}, m_e and m_{eqcal} are respectively the masses of the fuel, the water in the calorimeter and the equivalent water in the calorimeter.

CP is the heat capacity of water (4,180 J/kg. K).

$(T_F - T_O)$ is the difference between the temperatures of the water and the calorimeter during the experiment.

Having experimentally obtained the gross calorific values (PCS) of our wastes, we deduce their respective net calorific values (PCI) using equation (12) from[22] below:

$$PCI = PCS - 0.225 \times H \tag{12}$$

With:

H is the percentage by mass of hydrogen (H = % H) contained in the waste sample, such that H = (% Hu)/9.

% Hu is the moisture content of the waste.

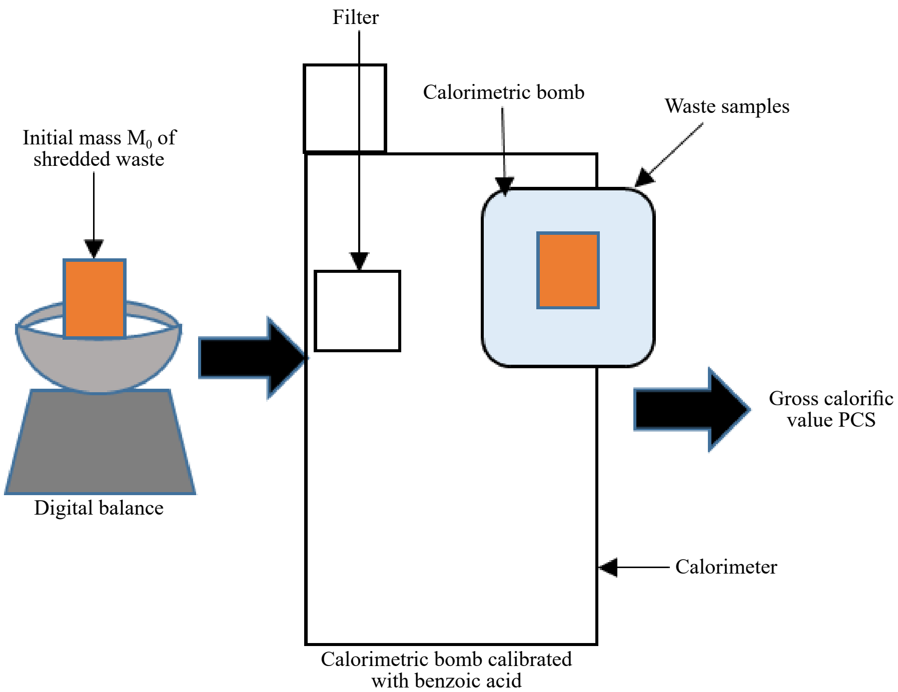


Figure 5. Diagram for determining the gross calorific value (PCS) of waste

Figure 5 above shows the diagram used to determine the gross calorific values (PCS) of the wastes studied.

2.4 *Determining the temperature variation ΔT of each agricultural waste product*

Using a digital thermometer connected to an electric wire, we record the temperature of our waste inside the boiler during combustion. After several repeated combustion tests, we found that, on average, the combustion of our agricultural waste produces steam at a temperature of Tmin = 350 °C. So, in our experimental study of the combustion of our waste, we assumed that the initial temperature was 350 °C (for the study of the comparison of the variation in the temperature of our waste during combustion).

2.5 *Determining the amount of heat Q released by each agricultural waste product*

The combustion of a mass of m = 0.50 g of each of the residues studied in our adapted boiler was carried out in the laboratory. Under the conditions of our experiment, we determined the amount of heat released by the biomass of each of the agricultural residues studied according to equation (13) for the condensation boilers below:

$$Q = m_{comb} \times PCS = (m_{ini} - m_{final}) \times PCS \tag{13}$$

With:

Q quantity of heat released by each of our agricultural residues in MJ.

PCS gross calorific value in MJ/kg.

m_{comb} fuel mass.

m_{ini} and m_{final} are respectively the initial and final masses of each waste when burnt in our adapted boiler.

2.6 *Determine the quantities of CO_2 gases emitted during the combustion of agricultural waste in our boiler*

The quantities of CO_2 gas emitted into the atmosphere during the combustion of agricultural waste in the boilers were determined using an accurate METERK electronic detector placed at a regulated distance of at least 1 m from the boiler. The measurement of the quantity of CO_2 gas in the normal atmosphere (air) in the absence of combustion is 400 ppm.

3. Results and discussion

3.1 *Results of the physico-chemical properties of the waste studied*

3.1.1 *Results of the physico-chemical properties of the waste studied obtained using approximate analyses*

Table 1 shows the physicochemical properties of the waste studied, obtained using the following approximate analyses: moisture content (% Hu), ash content (% Ash), organic matter or volatile dry matter content (% OM), fixed organic carbon content (% CF).

Table 1. Physico-chemical properties of the waste studied, obtained by approximate analyses

Samples	Moisture content (% Hu)	Ash content (% Ash)	Organic matter content (% OM)	Organic carbon content (% CF)
Oil palm fibres	3.60	18.80	81.20	47.07
Sugar cane bagasse	24.78	9.69	90.31	52.35
Cocoa cortex	43.12	23.88	76.12	44.12

Figure 6 shows that cocoa cortex has the highest moisture content (43.12%), followed by sugarcane bagasse with a high moisture content (24.78%). Next, palm fibres are the driest, with only 3.6% moisture. In general, biomass from agricultural residues is moderately moist. Good pre-treatment (grinding and drying) of our waste before combustion in boilers is therefore essential for efficient energy production.[23,24] The organic matter content (% OM) of this waste varies (from 76.12% to 90.31%). This means that burning this waste will produce considerable quantities of greenhouse gases such as CO_2, CH_4 and N_2O, which are also accompanied by the release of pollutants such as fine particles PM_{10} and $PM_{2.5}$ and CO gas (toxic), which is dangerous to human health.[25] The ash content (% ash) of this waste varies considerably (from 9.69% to 23.88%). This shows that burning our waste will produce a certain amount of ash which, because of its alkali metal content, could cause problems (agglomeration, corrosion, clogging) in combustion boiler furnaces.[26] The ash produced by the combustion of these agricultural residues can be used to make bio-fertilisers, which are important for improving agricultural soils.[27,28]

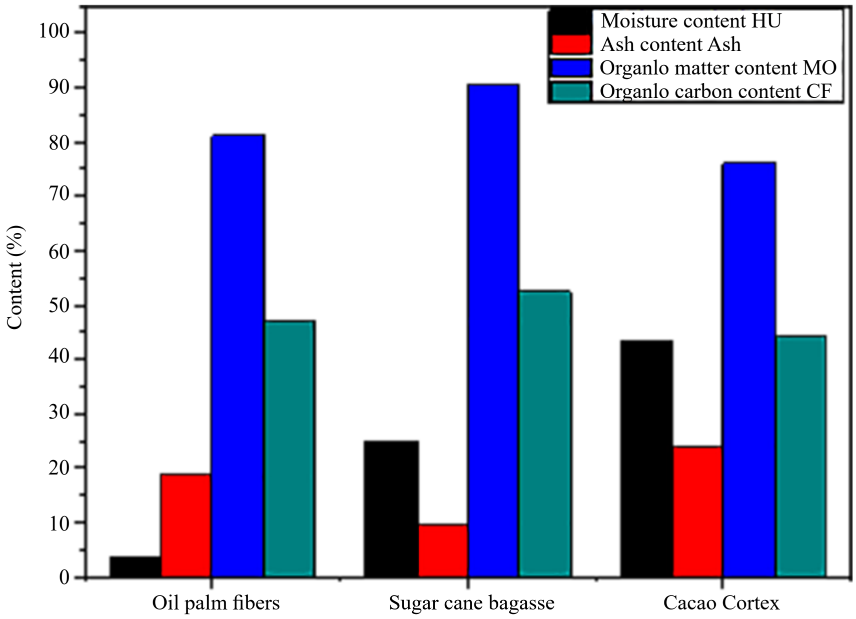


Figure 6. Comparison of the physico-chemical properties of the waste studied obtained by approximate analyses

3.1.2 *Results of the physico-chemical properties of the waste studied obtained using structural analyses*

Table 2 shows the physico-chemical characteristics of the waste studied, obtained using structural analyses: fibre content F (%), cellulose content C (%), hemicellulose content H (%) and lignin content L (%).

Table 2. Physico-chemical properties of the waste studied, obtained by structural analysis

Samples	Extraction rate (%)	Hemicellulose (%)	Lignin (%)	Cellulose (%)	Fibres (%)
Oil palm fibres	15.23	11.71	27.05	55.91	94.67
Sugar cane bagasse	7.51	21.91	17.80	42.29	82.00
Cocoa cortex	35.70	21.87	8.26	32.74	62.87

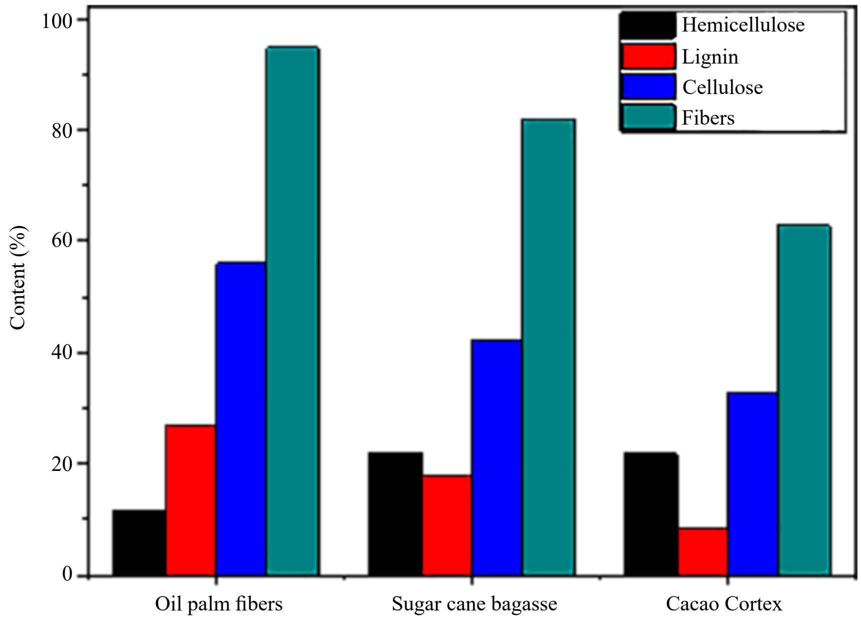


Figure 7. Comparison of the physico-chemical properties of the waste studied using structural analyses

Figure 7 shows the large amounts of fibre in the agricultural waste studied, ranging (from 62.87% to 94.67%) linked to lignins ranging (from 8.26% to 27.05%) and celluloses ranging (from 32.74% to 55.91%). The oil palm fibres with the highest fibre content (94.67%) burn faster and more efficiently than the other waste products studied. This is justified by the fact that the higher the fibre content (%), the drier the fuel (low humidity). This is in line with the results obtained, which show that palm fibre has the lowest moisture content (3.6%). This can be explained by the fact that the lignin and cellulose contained in waste-derived biomass contribute to the rigidity, mechanical strength and hydrophobicity of the cells. On the other hand, the moisture contained in the waste must be combated to ensure good combustion.[29] Nevertheless, it has to be said that the wastes studied make very good fuels, given their high fibre content (from 62.87% to 94.67%), which was verified during experimental combustion in the boiler, where each residue of agricultural material was properly treated (dried and crushed) ignites easily and produces a very large amount of heat.

Finally, with regard to the study of the physicochemical properties of this waste, it should be remembered that its moisture content (from 3.6% to 43.12%) and ash content (from 9.69% to 23.88%) could reduce the production of energy from the combustion of this waste. On the other hand, the high fibre content (from 62.87% to 94.67%) of these wastes, combined with their high lignin (from 8.26% to 27.05%) and cellulose (from 32.74% to 55.05%) content, will favour increased energy (heat) production from the combustion of these biomasses.[30] This is in line with the results obtained, since during the combustion of the agricultural residues studied, their convection and thermal radiation temperatures vary (from 350 °C to 630 °C). It is therefore necessary to use the best combustion devices and methods, as the quality and quantity of gaseous emissions and ash are linked to the physical and chemical properties of the fuels.[31,32,33] These approximate and structural analyses have shown that the physical and chemical properties of the agricultural residues studied vary from one to another.[34]

3.2 *Results of calorific values and quantities of heat produced by the combustion of each agricultural waste studied*

Table 3 shows the gross calorific values (PCS), net calorific values (PCI) and quantities of heat Q produced by the combustion of each agricultural residue studied.

Table 3. Energy generated by the waste studied[11]

Samples	Oil palm fibres	Sugar cane bagasse	Cocoa cortex
PCS (MJ/kg)	28.46	23.69	37.66
PCS (kWh/kg)	7.906	6.581	10.461
PCI (MJ/kg)	28.459	23.684	37.649
PCI (kWh/kg)	7.905	6.579	10.458
Quantity of heat released Q (kJ)	14.23	11.845	18.83
Quantity of heat released Q (Wh)	3.953	3.292	5.231

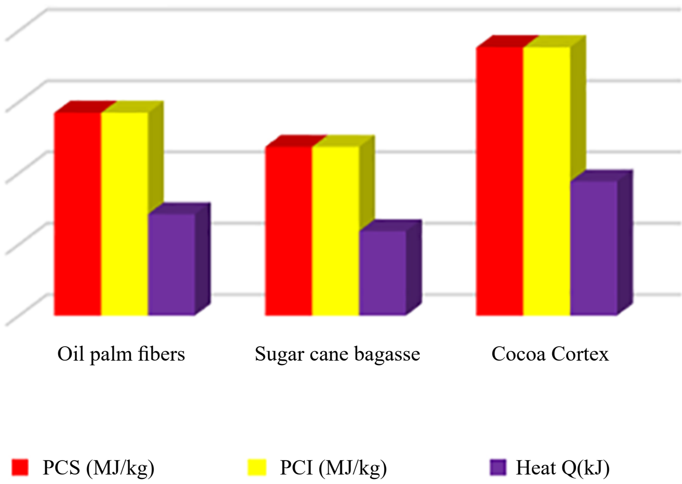


Figure 8. Comparison of agricultural waste energy in joules (J)

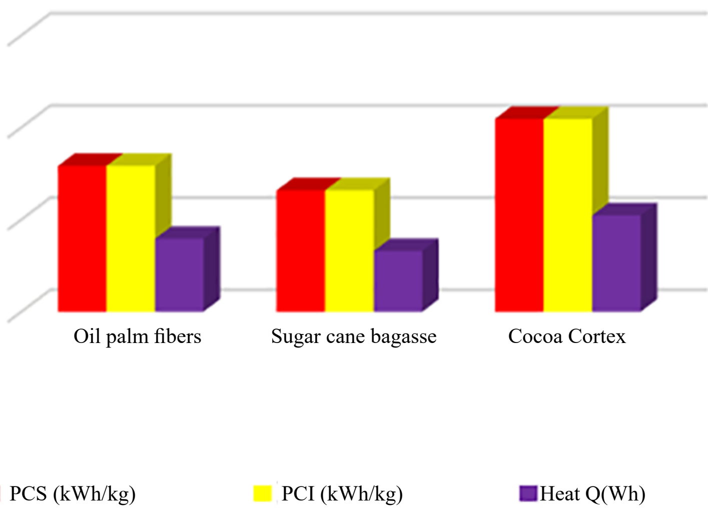


Figure 9. Comparison of agricultural waste energy in Wh

Figures 8 and 9 show that the cocoa cortex has a net calorific value (37.649 MJ/kg or 10.458 kWh/kg) and a greater quantity of heat released (18.83 kJ or 5.230 Wh) than the other two wastes. For the combustion of a small quantity (0.5 g) of each of the agricultural wastes studied, a large quantity of heat is produced, vary (from 11.845 kJ to 18.83 kJ) or (from 3.290 Wh to 5.230 Wh). Thus the large values of net calorific values vary (from 23.684 MJ/kg to 37.649 MJ/kg) or (from 6.579 kWh/kg to 10.458 kWh/kg) and the large quantities of heat released varying (from 11.845 kJ to 18.83 kJ) or (from 3.290 Wh to 5.230 Wh) produced by the combustion of a very small mass (0.5 g) of each of our agricultural residues. Prove that the agricultural residues studied are potential sources of energy and very good fuels for producing large quantities of heat that can be converted into electricity by turbines connected to alternators using electromagnetic induction phenomena. This confirms that for the production of clean (healthy) and renewable energy (heat and/or electricity), the biomass of the agricultural waste studied, used as a fuel through its combustion, can gradually replace fossil fuels.[35,36] In fact, the agricultural residues studied have net calorific values close to those of certain fossil fuels such as natural gas (16 kWh/kg), fuel oil (12 kWh/kg) and coal (8 kWh/kg).

3.3 *The different temperature variations ΔT of each of the agricultural residues during combustion*

Table 4 shows the different temperature variations of the agricultural residues studied during their combustion. The results in Table 4 show that when 0.5 g of each agricultural waste is burnt, the temperatures vary (from 350 °C to 630 °C). The average temperature difference is considerable (250 °C). This confirms that these agricultural residues produced a very large quantity of heat during combustion. The agricultural residues studied are therefore very good fuels.

Table 4. Temperature variations in the waste studied during combustion

Samples	Initial temperature Tmin (°C)	Final temperature Tmax (°C)	Temperature variation ΔT (°C)
Oil palm fibres	350	630	280
Sugar cane bagasse	350	615	265
Cocoa cortex	350	555	205

3.4 *The different quantities of gaseous CO_2 released by each of the wastes studied*

The results of measurements of the quantities of gaseous CO_2 emitted during the combustion of each agricultural waste in the boiler are presented in Figure 10 below.

Figure 10 shows that there is a low release (from 439 ppm to 447 ppm) of CO_2 (reference gas for greenhouse gases) during the combustion of this agricultural waste. This means that the combustion of this agricultural waste was carried out under good conditions, with good efficiency (complete combustion), given the high levels of total organic carbon (from 47.07% to 52.35%) and the large quantities of heat released (from 11.845 kJ to 18.83 kJ) or (3.290 Wh to 5.230 Wh) produced by the combustion of a very small mass (0.5 g) of each of our biomasses. In terms of environmental impact, it was important to determine the quantities of CO_2 gas (from 439 ppm to 447 ppm) emitted by the combustion of our agricultural waste. Recent studies have shown that despite the fact that plants absorb 30% of the world's CO_2 during their growth, this is no longer sustainable.[37] In recent years, the global increase in greenhouse gases (atmospheric CO_2), linked to global warming caused by human activities, could prevent plants from absorbing as much CO_2 as possible in order to protect our planet Earth. Finally, according to this study, cocoa cortex is the best fuel because it has the highest net calorific value (37.649 MJ/kg or 10.458 kWh/kg) and emits little CO_2 gas (447 ppm) like the other two wastes. But in general, the agricultural residues studied produce a considerable amount of energy (from 11.845 kJ to 18.83 kJ) or (from 3.290 Wh to 5.230 Wh) with low CO_2 emissions (from 439 ppm to 447 ppm) because 30% of the CO_2 emitted by the combustion of these agricultural residues will be absorbed by the plantations.[37]

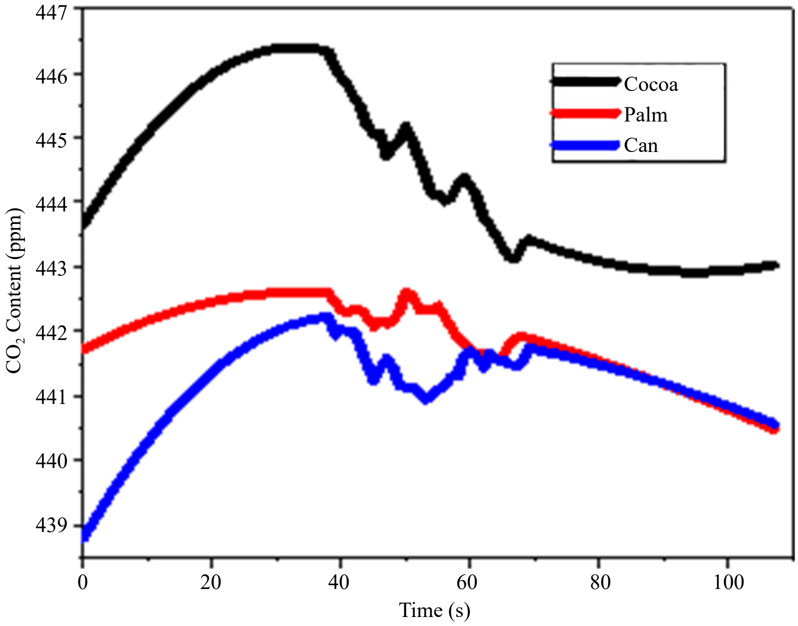


Figure 10. Comparison of CO_2 emissions from waste study

4. Conclusion

This study used a bomb calorimeter to determine the upper and lower calorific values of the agricultural waste studied, which are close to those of fossil fuels. Cocoa cortexes were found to be the best fuels due to their higher lower calorific values and low CO_2 emissions. The most important details of this work are the results obtained from the approximate and structural analyses of the physico-chemical properties of the agricultural residues studied, which are very important and linked to the quality and quantity of gaseous emissions, ash and particular matter in the atmosphere during the combustion of this agricultural waste. The results showed that these biomasses were good fuels for the production of energy (heat and electricity) by direct combustion, and that the small quantities of CO_2 gases emitted into the atmosphere during the combustion of this waste had to be taken into account. Finally, this study will provide credible information on the physicochemical properties of these agricultural residues to public and private decision-makers worldwide, encouraging them to use these biomasses as fuels in cogeneration units to produce energy (heat and/ or electricity).

The authors also plan to carry out a life cycle analysis (LCA) to determine the various gases and pollutants emitted during the combustion of this agricultural waste. Finally, they plan to use co-firing to achieve high energy efficiency and reduce greenhouse gas and particulate matter emissions.

Conflict of interest

The authors declare there is no competing financial interest.

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