Towards Electricity from the Combustion of Agricultural Waste in Boilers with Low CO₂ Emissions

Yao Modeste Boni¹*, Amal Bouich², Sampson Oladapo Oyedele¹, Noureddine El Messaoudi³, Bernabé Mari Soucase², Aka Boko¹

¹Fundamental and applied physics laboratory of the basic and applied science training and research unit UFR SFA, Université Nangui Abrogoua (UNA) Abidjan, Côte d'Ivoire
²Institute of Design for Automated Manufacturing and Production, Polytechnic University of Valencia, Spain
³Laboratory of Applied Chemistry and Environment, Faculty of Sciences, Ibn Zohr University, Agadir 80000, Morocco
Emails: boniyaomodeste@gmail.com

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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 CO₂ 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 CO₂ 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 CO₂ gaseous emissions
1. Introduction

The world’s energy needs linked to population growth are driving industrial growth, sometimes despite the environmental impact of greenhouse gas emissions. 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. 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. 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. 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. In physical conversion processes, biomass is transformed into a solid fuel by densification methods (grinding, sieving, drying and pelleting). In thermochemical conversion processes, heat and chemical catalysts are used to transform biomass into high-energy products (heat, bio-oil, bio-char and gas). In biochemical processes, enzymes and micro-organisms are used to transform biomass into energy products (bioethanol and biogas). 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). The combustion of agricultural waste biomass to
produce energy (heat) can be represented by the following general equation (1) taken from.\(^\text{10}\)

\[
C_{x}H_{y}O_{z}N_{a}S_{d} + \left(a + \frac{b}{2} + e - c\right)(1+x)(O_{2} + 3.8N_{2}) \rightarrow aCO_{2} + bH_{2}O + \left(a + \frac{b}{2} + e - c\right)(1+x)(3.76 + d)N_{2} + \left(a + \frac{b}{2} + e - c\right)O_{2} + eSO_{2}
\]

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\(^\text{11}\) 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.\(^\text{11}\) 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,\(^\text{12}\) see Figure 1 below.

![Agricultural waste studied](image)

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: 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).

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. 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:

\[
\%Hu = \left( \frac{M_0 - M_1}{M_0} \right) \times 100
\]  

(2)

With:

<table>
<thead>
<tr>
<th>% Hu: Moisture content.</th>
</tr>
</thead>
<tbody>
<tr>
<td>M₀: initial mass of sample before drying (50 g).</td>
</tr>
<tr>
<td>M₁: final mass of the sample after drying at 105 °C.</td>
</tr>
</tbody>
</table>

![Figure 2. Moisture content diagram (% Hu)](image)
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)](image)

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).
\[ M_1: \text{mass of waste at 105 °C.} \]
\[ M_2: \text{mass of waste at 550 °C.} \]

### 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).

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

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.\(^\text{17,18,19}\) 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 $\text{SO}_4^{2-}$ 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:

$$L(\%) = \frac{m_6 \times (100 - E_x)}{m_5}$$  

(8)

### 2.2.2.4 Cellulose content C (%)

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

$$C(\%) = 100 - E_x - H(\%) - L(\%)$$  

(9)

### 2.2.2.5 F-fibre content (%)

The fibre content $F$ (%) is determined by formula (10) of:

$$F(\%) = H(\%) + C(\%) + L(\%)$$  

(10)

Figure 4 below shows the diagram used to determine 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:

\[ m_{\text{comb}} \times PCS = (m_e + m_{\text{equiv}}) \times CP (T_F - T_0) \]  

With:

- \( m_{\text{comb}} \), \( m_e \) and \( m_{\text{equiv}} \) 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).
- \( (T_F - T_0) \) 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 below:

\[ PCI = PCS - 0.225 \times H \]

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 above shows the diagram used to determine the gross calorific values (PCS) of the wastes studied.
2.4 Determining the temperature variation $\Delta T$ 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 $T_{\text{min}} = 350$ $^\circ$C. So, in our experimental study of the combustion of our waste, we assumed that the initial temperature was 350 $^\circ$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:

$$Q = m_{\text{comb}} \times PCS = (m_{\text{ini}} - m_{\text{final}}) \times PCS$$  \hspace{1cm} (13)

With:
- $Q$ quantity of heat released by each of our agricultural residues in MJ.
- $PCS$ gross calorific value in MJ/kg.
- $m_{\text{comb}}$ fuel mass.
- $m_{\text{ini}}$ and $m_{\text{final}}$ 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>
<thead>
<tr>
<th>Samples</th>
<th>Moisture content (% Hu)</th>
<th>Ash content (% Ash)</th>
<th>Organic matter content (% OM)</th>
<th>Organic carbon content (% CF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil palm fibres</td>
<td>3.60</td>
<td>18.80</td>
<td>81.20</td>
<td>47.07</td>
</tr>
<tr>
<td>Sugar cane bagasse</td>
<td>24.78</td>
<td>9.69</td>
<td>90.31</td>
<td>52.35</td>
</tr>
<tr>
<td>Cocoa cortex</td>
<td>43.12</td>
<td>23.88</td>
<td>76.12</td>
<td>44.12</td>
</tr>
</tbody>
</table>

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.\textsuperscript{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$_2$O, 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.\textsuperscript{24} 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.\textsuperscript{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.\textsuperscript{27,28}

![Figure 6. Comparison of the physico-chemical properties of the waste studied obtained by approximate analyses](image)

### 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>
<thead>
<tr>
<th>Samples</th>
<th>Extraction rate (%)</th>
<th>Hemicellulose (%)</th>
<th>Lignin (%)</th>
<th>Cellulose (%)</th>
<th>Fibres (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil palm fibres</td>
<td>15.23</td>
<td>11.71</td>
<td>27.05</td>
<td>55.91</td>
<td>94.67</td>
</tr>
<tr>
<td>Sugar cane bagasse</td>
<td>7.51</td>
<td>21.91</td>
<td>17.80</td>
<td>42.29</td>
<td>82.00</td>
</tr>
<tr>
<td>Cocoa cortex</td>
<td>35.70</td>
<td>21.87</td>
<td>8.26</td>
<td>32.74</td>
<td>62.87</td>
</tr>
</tbody>
</table>
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. 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. 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. These approximate and structural analyses have shown that the physical and chemical properties of the agricultural residues studied vary from one to another.

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

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

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. 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 $\Delta T$ of each of the agricultural residues during combustion

Table 4 shows the different temperature variations of the agricultural residues studied during their combustion.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Initial temperature $T_{\text{min}}$ (°C)</th>
<th>Final temperature $T_{\text{max}}$ (°C)</th>
<th>Temperature variation $\Delta T$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil palm fibres</td>
<td>350</td>
<td>630</td>
<td>280</td>
</tr>
<tr>
<td>Sugar cane bagasse</td>
<td>350</td>
<td>615</td>
<td>265</td>
</tr>
<tr>
<td>Cocoa cortex</td>
<td>350</td>
<td>555</td>
<td>205</td>
</tr>
</tbody>
</table>

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.

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. 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
CO₂ emitted by the combustion of these agricultural residues will be absorbed by the plantations.\textsuperscript{17}

Figure 10. Comparison of CO₂ 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 CO₂ 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 CO₂ 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.

References