Energy recovery from agri-food processing waste using a thermal process : Formulation and characterization of biofuels from *Citrus sinensis* and *Manihot esculenta* peelings

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ABSTRACT (ARIAL, BOLD, 11 FONT, LEFT ALIGNED, CAPS)

This work proposes an energy recovery from agri-food waste through its transformation into biofuel. The agri-food wastes concerned in this work are cassava and orange peels and cassava wastewater, which served as a binder. The carbonization phase made it possible to obtain 34.68% dust for the orange peels and 29.06% for the cassava residues. These dusts made it possible to propose two biofuel formulas : L8M92, composed of 8% dry matter powder of the binder and 92% cassava peeling powder ; and L8O92, composed of 8% dry matter powder of the binder and 92% orange peel powder. The characterization of the formulated biofuels made it possible to note that biofuels based on orange peel contain 8.88% ash, a fixed carbon rate of 36.07%, and a Lower heating value (LHV) of 21.54 MJ/kg. Biofuels based on cassava peels contain 19.65% ash and 36.59% fixed carbon, with an LHV of 21.13 MJ/kg. The controlled combustion test (CCT) tests using the formulated biofuels showed that the CO and PM2.5 emission factors are, respectively, 22.38 g/kg and 1.38 g/kg for the biofuel from peelings. Orange, 22.05 g/kg, and 1.45 g/kg for biofuel from cassava peelings. From these results, it is concluded that biofuels formulated from cassava and orange are recoverable, and they have CO and PM2.5 emission factors close to those of charcoal. These biofuels have an interesting energy content with fairly modest CO and PM2.5 emission factors, close to those obtained from charcoal. Also, the characteristics of the formulated biofuels are in the same order of magnitude as those in the literature. These results indicate that cassava and orange waste can be used to contribute to the diversification of the energy supply through biofuel production. However, further work is needed to improve these results.

Keywords: Waste; Biofuel, Energy, Emission factor

1. INTRODUCTION

The demographic growth experienced by the world in the course of the last century, as well as industrial development and accelerating urbanization, have been accompanied by an increased demand for energy, especially oil, which is considered the primary source of energy [9] [20]. Faced with this rising demand, fossil fuel reserves will not last forever, and oil shortages will gradually set in. This will have a negative impact on the accessibility of energy, which is a vital element for mankind and the environment. As stated in Goal 7 of the Sustainable Development Goals (SDGs), "Energy is at the center of almost every major challenge and opportunity facing the world today. Whether we're talking about jobs, security, climate change, food production or income growth, access to energy for all is essential. Working in this direction is particularly important, as it has a direct effect on the ability to achieve other SDGs. Focusing on universal access to energy, increased energy efficiency and increased use of renewable energy through new technologies and business opportunities is crucial to creating more sustainable and inclusive communities and resilience to environmental challenges such as climate change." Indeed, in sub-Saharan Africa, traditional energies, most notably wood, are the most widely used in heat production, as around 792 million people used traditional biomass for cooking in 2014 [16]. In Burkina Faso, biomass remains the main source of domestic energy for both urban and rural populations. In 2002, wood energy, along with charcoal, formed almost 90-97% of household energy consumption [3,4]. In rural areas, almost all the energy consumed for cooking comes from biomass. This rate is not likely to decrease with population growth, and its impact on the environment is not negligible. The excessive use of wood undoubtedly leads to a reduction in vegetation cover, the advance of the desert, and a weakening of the environment. Also, due to the effect of CO2 on the environment and global energy problems, the replacement of fossil fuels has become necessary [9] [20].

In addition, the operations of agri-food processing industries generate large quantities of solid waste (peelings, hulls, etc.), liquid waste (wastewater) and emissions in their transformation processes. These include (i) the cassava and orange processing industries, whose wastewater and peel discharges are a problem in many developing countries [11].

According to the Food and Agriculture Organization of the United Nations (FAO), the world produced around 121 million metric tons of cassava roots in 2017, with Africa alone producing 55% of the global output [3]. Of this production, 25 to 37% is lost as peel ; 14.51% as pulp, and around 150 to 600 liters of fermented water are generated per ton of processed cassava tuber (de Carvalho et al., 2018). This fermented water, which is generally released into the environment, is harmful to fauna and flora, as well as to neighbors (health risks and unpleasant odors). It is important to note that the by-products of agri-food processing represent an energy source whose valorization could help improve access to energy [18]. According to (Glanpracha and Annachhatre, 2016) [11] and (Wadjeam et al., 2019) [17], agro-industrial cassava residues, including cassava pulp, cassava wastewater, and cassava stalks, have attracted research attention for their valorization in the form of biogas and/or biofuel.

The problem that arises in this study is to find another environmentally friendly fuel. This is the background to the present article, whose general aim is to reduce deforestation caused by the heavy use of firewood and charcoal manufacture and even eliminate the use of charcoal, as emphasized by COP26, in order to replace it with green charcoal. To this end, a raw material characterization, a biofuel formulation and a feasibility study of a biofuel production unit in relation to the availability of raw materials and the size of the foreseeable market will be proposed.

2. MATERIAL AND METHODS

2.1. Presentation of the study area

Burkina Faso is a landlocked Sahelian country situated in the loop of the Niger River, with a surface area of 274,200 km^2. It is divided into 13 administrative regions and 45 provinces, one of which is Kadiogo, with the city of Ouagadougou as its capital. In 2019, Burkina Faso was home to 20,505,155 people, of whom 68.5% (versus 64.9% in 2018) of households use wood as cooking fuel, 11.2% use coal, and 21% use gas [8]. There are two (2) seasons of unequal length : a rainy season lasting 3 to 4 months (June to September) and a dry season lasting 8 to 9 months (October to May). Temperatures generally range from 24 to 34°C in July. Average annual rainfall ranges from 1,300 mm in the south to less than 400 mm in the north. Ouagadougou, the capital of Burkina Faso, is located in the Sahel-Sudanian zone at 12°20' north latitude and 1°30' east longitude. Its average altitude is 300 meters. With a population of 2.5 million in 2015, its population has risen to 3,030,384 in 2019 [8] . In recent years, Burkina Faso has seen an upward trend in economic activity, with average annual growth in Gross Domestic Product (GDP) of 5.6% over the period 2011–2017 [8]. This situation has led to a sharp increase in energy demand, particularly for electricity. The energy sector is characterized by low coverage of the national electricity grid (35.58% at December 31, 2017) and a strong predominance of biomass (80% from 2013 to 2018). 65.6% of households in Burkina Faso use firewood with a single hearth to cook food. A further 16.1% use gas or biogas, and 10.8% use charcoal. Firewood is used by 83.5% of households in rural areas. In urban areas, gas or biogas is used by 41.5% of households [8]. 86% of the working population is employed in the agricultural sector. The main crops produced are 4,953,257 metric tons of cereals, 563,331 metric tons of oil seeds, 216,291 metric tons of vegetables, 111,737 metric tons of tubers, and 77,183 metric tons of fruit. In recent years, tubers, and more specifically, cassava, have attracted particular interest. Its production in the country has increased from 17,240 metric tons in 2008 to 128,772 metric tons in 2016 and to over 234,000 metric tons in 2018 [1]. Burkina Faso's agro-industrial activities generate huge quantities of waste, whose recovery is still timid. For example, some 40,000 metric tons of mango waste, 30,000 metric tons of Shea cake, and 4,500 to 6,000 metric tons of cashew nutshells are produced each year [12, 13].

Fig. 1. Presentation of study area

2.2 Materials used

2.2.1. Muffle furnace

Volatile organic matter and total volatile solids were determined using a Nabertherm muffle furnace with a temperature range up to 1100°C.

Fig. 2. Muffle furnace used to determine the volatile matter content of samples.

2.2.2. Balance

A Citizon-type balance with a maximum capacity of 210 g and an accuracy of (0.0001 g) was used to weigh the substrates.

Fig. 3. Balance used to determine sample mass

2.2.3. Calorimeter

The calorimeter is adiabatic and enables calorific values to be determined. Figure 4 shows the Parr 6200 calorimeter used in our study.

Fig. 4. Calorimeter

2.2.4. Description of the Laboratory Emission Measurement System (LEMS)

The measurements of the performances of the fireplaces and the emissions are carried out using a device conceived by the American laboratory "APROVECHO Research Center (ARC)" : the "Laboratory Emission Measurement System (LEMS)". This device allows the collection of Black Carbon (BC) emissions as well as other GHG generated by combustion with a fireplace during a standardized water boiling test. Figure 3 shows the experimental setup for the fireplace boiling water test. This device includes (1) a flue gas chimney, (2) a cyclone. A filter is placed in the cyclone to collect the black particles that are released during combustion, and this is connected to a fan to draw in the flue gas. Another cyclone is available for the measurement of particles smaller than 2.5 microns ($PM_{2.5}$) ; (3) a sampling port ; (4) a sensor box, which is a flue gas analyzer equipped with a temperature sensor and CO and CO_2 measurement ; (5) a suction pump that draws the black particles to the cyclone ; and (6) a gas separator : A particle separator has been installed to separate the fine particles of coal, ash and aerosols contained in the gas.

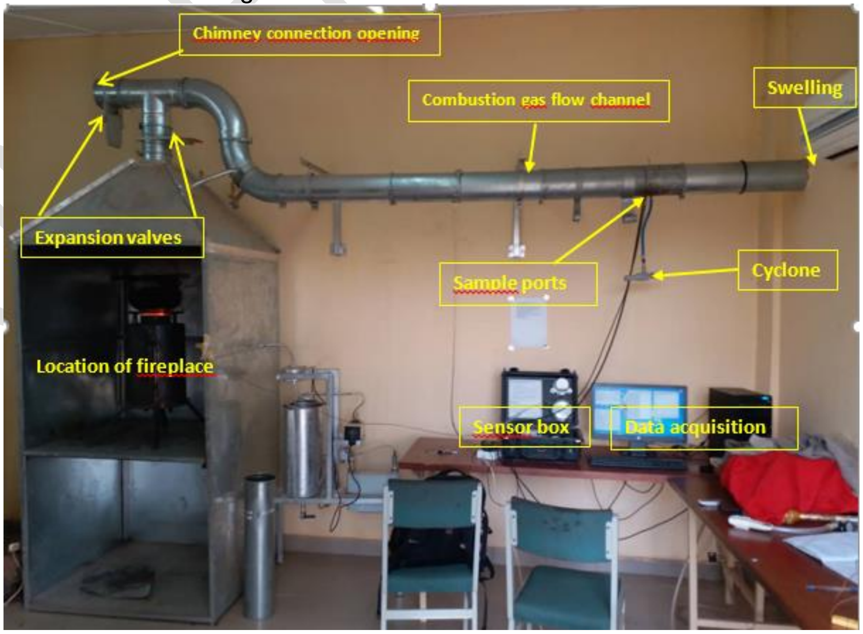

Fig. 5. Laboratory Emission Measurment System (LEMS)

2.3 Biomass resources

Agricultural residues are the main biomass resource considered in this study. They exist in large quantities and are harvested every day in the various sections. So far, the only way to recycle peelings is to compost them for agricultural use. As far as orange peels are concerned, there is no known use at this stage of the study. Orange peels exist in large quantities and are piled up on the edges of markets where artisanal citrus fruit processors set up shop. Orange peel represents a weight of 20%.

2.4. Immediate biomass analysis

2.4.1. Determination of dry matter

Dry matter is determined in accordance with **NF ISO 11465 AFNOR X 90-029 (1994)** by drying in an oven at 105°C for 24 hours. The difference in weight corresponds to moisture loss, and the residue represents the dry matter content of the sample. The capsule is weighed after cooling in a desiccator. The dry matter content is determined by equation 1.

$$MS = \frac{Mf - Mv}{Mi - Mv} \times 100 \qquad \text{(Eq1)}$$

Mf : final mass of crucible and sample after drying at 105°C (g) ; Mv : mass of empty crucible (g) ; Mi : mass of crucible and sample before drying (g) and MS : dry matter (g). From equation 1, we obtain the moisture content (% H) of the substrate, which is :

$$\%H = 100 - MS(\%) \qquad \text{(Eq2)}$$

2.4.2. Determination of organic matter content

The organic matter content of samples is measured in accordance with **NF U 44160 (1985).** The previously dried samples are calcined in a kiln at 550°C for 4 hours in an oxidizing atmosphere. The organic matter is consumed, and the residual matter constitutes the mineral matter. The loss of mass, in relation to the quantity of dry matter, corresponds to the rate of volatile matter.

$$MO(\%) = \frac{Mf' - Mv}{Mf - Mv} \times 100 \qquad \text{(Eq3)}$$

Mf' : final mass after calcination at 550°C ; Mf : final mass after drying at 105°C ; MO : organic matter.

2.4.3. Determination of volatile matter content

Volatile organic matter is determined in accordance with **AFNOR/X 34 B N°289**. A test sample of the general analysis sample is heated without contact with air at 900°C ± 10°C for 7 minutes. The percentage of volatile matter is calculated from the loss in mass of the test portion after deduction of the loss in mass due to moisture. The rate of volatile matter is determined by the loss of mass during heating, using relationship (5) to estimate the rate of volatile matter.

2.4.4. Determining total ash content

The ash content is the amount of solid residue remaining after complete combustion of a fuel. Ash content is measured in a muffle furnace, and is obtained by calcining a sample at 550°C until white or gray ash is obtained. It is determined in accordance with ISO 21656. The content is calculated using relationship (4) :

$$CT = \frac{(m_3 - m_1)}{(m_2 - m_1)} \times 100 \qquad (Eq4)$$

Where CT : ash content (%) ; m_1 : mass of empty crucible (g) ; m_2 : mass of crucible before calcination (g) and m_3 : mass of crucible after calcination (g).

2.4.5. Determination of fixed carbon content

The carbon content determines the percentage of mineral elements contained in a dry mass of coal powder. This value is important because it is linked to the powder's ability to generate heat. The fixed carbon rate is not determined experimentally. It is deduced by difference on a dry basis according to equation (5) [20].

$$CF\ (\%) = 100 - (MV + CT) \qquad (Eq5)$$

Where : CF : fixed carbon content (%) ; MV : amount of volatile matter (%) ; CT : ash content (%).

2.4.6. Energy content

Energy content is the thermal energy released by the complete combustion of a unit mass of fuel. A distinction is made between two types of calorific value : (i) the higher heating value (HHV) is obtained when all the fuel has been converted into energy, including the water vapour released and the flue gases. It is determined experimentally using a calorimeter. The lower heating value (LHV) is the thermal energy released by the complete combustion of a unit mass of a fuel in the form of sensible heat, excluding the energy of vaporization of the water present at the end of the reaction. The difference between HHV and LHV represents the latent heat of condensation of the water vapour present in the flue gases. It can be deduced from the HHV by the following formula :

$$\mathrm{LHV} = \mathrm{HHV} - (\mathrm{m_{H2O}} \times \mathrm{L_v}) \qquad (\mathrm{Eq6})$$

m_{H2O}: The total mass of water, expressed in kg, released by the combustion of 1 kg of raw fuel. Lv : The latent heat of vaporization of 1 kg of water vapor, estimated at 2260 kJ.

2.5. Biomass carbonization

In the present study, the process used is partial combustion carbonization. In this process, the energy required for carbonization is provided by the combustion of part of the feedstock. To initiate carbonization, all that's needed is to activate the fire and then close it to prevent the entry of oxygen, which could counteract carbonization by promoting the formation of ash, which is detrimental to such production.

2.6. Biofuel formulation

The carbonized raw materials were crushed using an electric grinder, and to obtain a more valuable product, sieving was carried out manually. A 2-mm mesh screen was used. To ensure adhesion between the coal particles and the strength of the fuel briquettes, a binder was added. In our trial, mixing was carried out in a bowl, and cassava starch was used as the binder. The proportions used are 92% carbonized raw material and 8% binder by dry mass. Figure 6 shows the biofuel formulation stages.

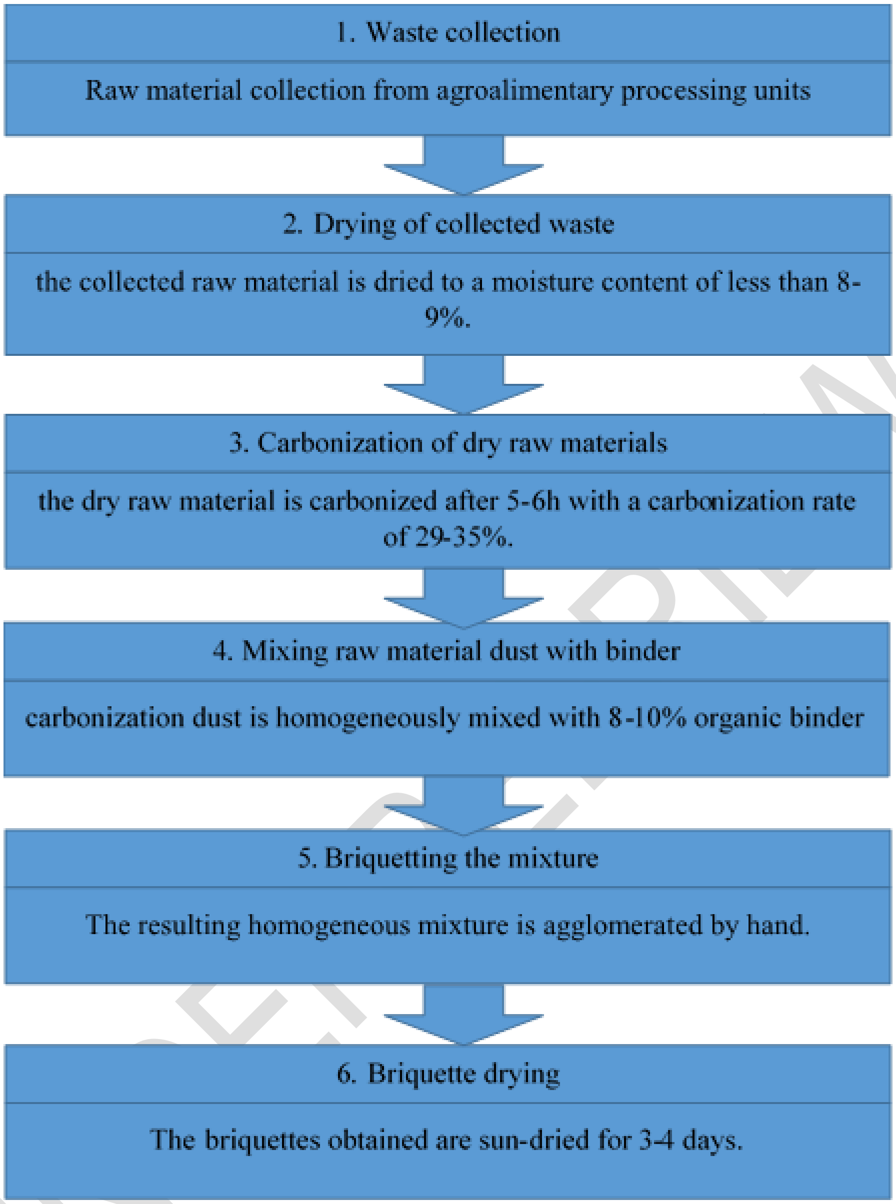

Fig. 6. Biofuel formulation stages

2.7. Combustion tests : Boiling Water Test

WBT Version 4.2.3 (Test d'Ebullition de l'Eau (TEE)) is used as a combustion test. The TEE is a simplified simulation of the cooking process [5]. It aims to measure the efficiency with which a household uses fuel to heat water in a pot and the emissions produced during cooking. The aim was to assess the combustion of the biofuels produced. The aim was to compare the time taken by these biofuels to boil the same quantity of water, the time taken to consume them, and also to assess the $PM_{2.5}$ and CO emission factors in comparison with charcoal.

2.8. Thermal efficiency

Thermal efficiency is calculated from the WBT. Thermal efficiency is the ratio between the amount of energy received by the water and the energy content of the fuel. It is determined by equation 7 [2]:

$$\eta = \frac{m_e \times c_e(Tf - Ti) + m_{ev} \times L_v}{m_b \times LHV} 100 \qquad (Eq7)$$

With $\boldsymbol{me}$: Mass of water (kg) $\boldsymbol{Ce}$: Heat capacity of water (4.186 kJ/kg/K) $\boldsymbol{Tf}$: Final temperature of water (°C) $\boldsymbol{Ti}$: Initial temperature of water (°C) $\boldsymbol{mev}$: Mass of water evaporated (kg) $\boldsymbol{Lv}$: Latent heat of evaporation of water (2260 kJ/kg) $\boldsymbol{mb}$: Mass of coal consumed (kg) LHV : Lower heating value of coal (kJ/kg) [15].

2.9. Economic viability of the biofuel industrialization project

The cost of a biofuel production plant can be classified into two main categories : (i) capital investment and (ii) operating or variable costs. Capital investment or fixed costs include : basic equipment, handling, raw material storage and plant layout (land, road, transport, building, etc.). Fixed costs depend mainly on technology, plant size and biomass feedstock [9].

Variable costs include biomass or feedstock collection, maintenance, product transport, labor, utilities, transportation, etc. The approximate percentage contributions of the various components to variable costs are shown in Table 1.

On the other hand, the concept of present value (NPV) can be used to evaluate the production price of a kilogram of biofuel in order to verify the value for money and profitability of an investment. The NPV is given by the following relationship [2] :

$$P = \frac{(1+i)^n - 1}{i \times (1+i)^n} \times A \qquad \text{(Eq7)}$$

With P present value ; A constant annuity and i the discount rate. For the discount rate we will use the value i=11.1%, corresponding to the addition of an interest rate of 10% and an inflation rate of 1.1%. This rate will be applied in the present study. The amortization period is set at seven (7) years in the present study.

Table 1. Capital and operating costs of the biofuel production plant

Section	**Quantity**	**Cost per unit (€)**	**Total cost (€)**
1. Investment costs			
Carbonizer	5	1524	7620
Manual press	2	305	610
Wheelbarrow	4	114	457
Small equipment	-	305	305
Acquisition of plot for unit installation	1	4573	4573
Building	1	2287	2287
Tricycle	1	1524	1524
Total 1			10518

2. Operating costs			
Producers salaries par year	8	1098	8784
Maintenance (5% of total 1)	-		526
Operating fuel	-	60000	1 098
Raw material			732
Total 2			10 610
Total			21 132

3. RESULTS AND DISCUSSION

3.1 Carbonization of raw materials

This section presents the results obtained, their analysis and a comparison with other results from similar studies. The TEE tests also made it possible to evaluate the particulate matter ($PM_{2.5}$) and CO emission factors for each of the proposed formulas. Figure 7 shows the temperature evolution during the carbonization of orange peel and cassava peel, respectively.

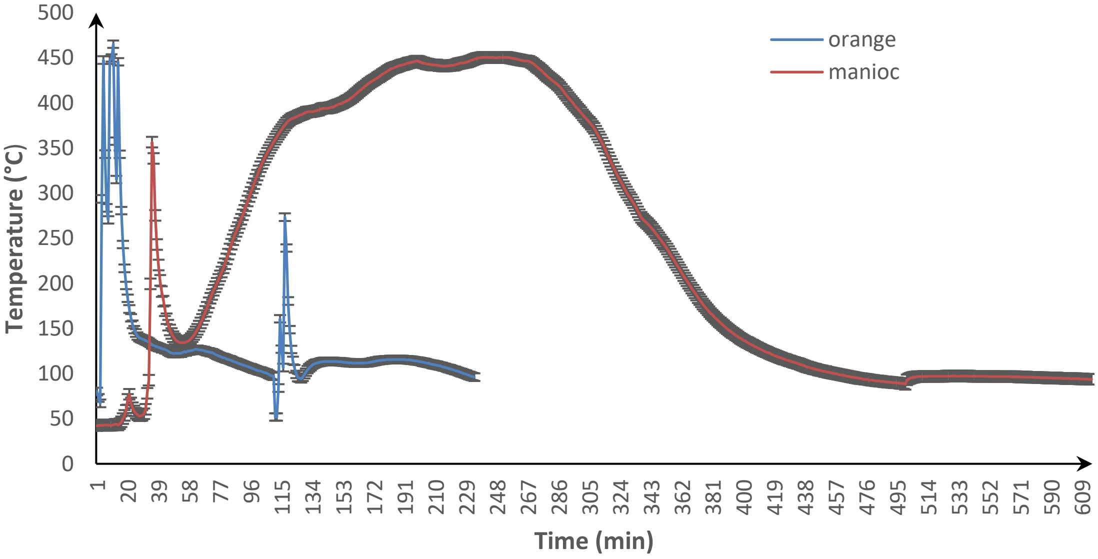

Fig. 7 : Evolution of carbonization temperature of cassava and orange peels

Orange and manioc peels were carbonized for approximately 3 hours and 5 hours, respectively. A rapid rise in temperature was observed in two stages : from 1 to around 20 min, with a temperature rise to over 450°C, and from 103 to 130 min, with a temperature rise to 273°C. This rapid rise in temperature results in a very short carbonization time, especially for orange peels. This can be explained by the nature of orange peels, which are full of oily matter. The second peak can be explained by a surge of oxygen when the carbonizer opened after 2 hours of operation and before the end of pyrolysis. The maximum temperature reached for both raw materials is over 450°C, confirming that carbonization has been effective, as they are close to the slow pyrolysis of wood (300–700 °C).

1. Carbonization rate

Table 2 shows the carbonization rates of the two formulas derived from cassava peelings, orange peelings, cashew shells and cotton stems.

Table 2 : Carbonization rate

Designation	Carbonization rate (%)	Authors
Orange peel	35	Current study
Cassava peelings	29	
Cotton stem	22	[15]
Cashew nuts	10.34-20.47	[15]

Orange peels have a carbonization rate of 35%, compared with 29% for cassava peels. The carbonization rates obtained are slightly higher than some similar results in the literature. These differences can be explained in part by the quality and nature of the raw material, but also by the insufficient carbonization quality in the present study (justified by the high volatile matter content of the biofuels obtained).

3.2. Results of immediate biofuel analyses

3.2.1. Biofuel density

Figure 8 shows the fuel formulas obtained. The raw materials used (cassava peel and orange peel) were used to formulate two biofuels, L8M92 and L8O92. These biofuels are composed of : (i) L8M92, composed of 8% dry binder base and 92% mass carbonized cassava peel powder ; and (ii) L8O92, composed of 8% dry binder base and 92% mass carbonized orange peel powder. These formulas have a density of 0.61 ±0.01g/cm^3 and 0.57±0.01g/cm^3 respectively, for L8M92 and L8O92.

a) *L8O92* b) *L8M92*

Fig. 8. Formulated biofuels : a) L8O92 and b) L8M92

These results show that cassava biofuels are denser than orange peel biofuels. This means they are more compact and thicker. Table 3 shows the ignition test times for the fuels.

Table 3 : Ignition times for biofuels

Fuels	Ignition time (s)
L8O92	15
L8M92	17
Wood charcoal	90

The ignition test consists of determining the ease of ignition of biofuels. The results of this test show that biofuels ignite more easily than charcoal. This can be explained by the presence of a significant amount of volatile matter (MV≥43%) and the low density of the biofuels. These results are in line with those reported in the characterization of sawdust-based fuels [17].

3.2.2. Physico-chemical characteristics of biofuels

Table 4 shows the physico-chemical characteristics of the biofuels formulated and those of other similar works in the literature.

Table 4. Physical and chemical characteristics

Fuels	**% H**	**% CT**	**%MV**	**% CF**	**HHV**	**LHV**	**Authors**
					MJ/kg		
L8O92	8.25±0.12	8.88±0.5	55.05±0.90	36.07	21.547±0.44	21.546±0.44	Current study
L8M92	7.33±0.29	19.66±3,39	43.75±0.51	36.59	21,133±0.74	21.132±0.74	
Wood charcoal	-	6.82±5	14.07	79.11	30.595±0.34	30.94±034	
Cashew nut shell charcoal	-	-	-	-	-	28.2	[15]
Raw cashew nut shell	12	-	-	44	-	23.58	[15]
Peanut shell charcoal	-	20.02	13.47	66.51	26.31	25.62	[15]
Corn cob charcoal	-	17.65	20.90	61.46	25.74	24.95	
Soya stalk charcoal briquette (BCTS)	-	35.61	9.52	39.62	-	21.22	[15]

The results show that formulated biofuels are less energetic (PCI ~ 21MJ/Kg) than charcoal (~30 MJ/kg). This is because the fixed carbon content of biofuels (~36%) is low compared with that of charcoal (79%). The high volatile matter content of formulated biofuels is linked to the use of starch as a binder, with an MV content of 99.83% [17]. In addition, the presence of mineral matter and impurities in the fuel results in a high ash content. L8O92 biofuel has an ash content of 8.88 ±0.5%, resulting in a low carbon content of 36.07%. L8M92, on the other hand, has a center content of 19.65%, giving it a carbon content of 36.59%. Furthermore, the large amount of volatile matter in the fuels produced is also partly due to the insufficient carbonization quality (34.68% for orange and 29.06% for cassava). Even though these analyses show that biofuels have a lower ICP than charcoal, it is important to note that the

ICPs of formulated biofuels are in the same order of magnitude as those of other biofuels reported in the literature. These include BCTS (21.22 MJ/kg), cashew nutshells (23.58 MJ/kg), peanut shell briquettes (25.6 20 MJ/kg) and maize cob briquettes (24.95 MJ/kg) [15]

3.2.3 Thermal efficiency

Figure 9 shows the controlled firing test.

Fig. 9. Controlled combustion test

This shows that biofuels ignite easily (ignition times 15 and 17 seconds respectively for L8O92 and L8M92). Table 5 shows the thermal efficiencies obtained with Burkina mixe stoves using formulated biofuels and charcoal as the reference fuel.

Table 5 : Thermal efficiency

Designation	Heat efficiency (%)	Authors
Wood charcoal	27	Curent study
L8O92	25	
L8M92	26	
Cashew nut shell charcoal	5.42-10.98	[15]
Wood charcoal	11.79-30.6	

The thermal efficiencies obtained with charcoal are of the same order of magnitude as those reported in the literature. It emerges that the use of biofuels formulated in the Burkina Mixte stove results in higher thermal efficiencies than with charcoal. This difference is partly explained by the fact that biofuels crumble during combustion, creating a perfect bond with the heat exchanger (kettle) and thus limiting convective heat loss.

3.3. Biofuel emission factors obtained

Table 6 shows the CO and PM2.5 emission factors obtained in the controlled TEE tests.

Table 6 : Emissions factors of biofuels

Fuels	Emission factor (g/MJ)	Emission factor (g/kg)

	$PM_{2,5}$	CO	$PM_{2,5}$	CO
L8O92	0.180	2.95	1.39	22.38
L8M92	0.174	2.63	1.46	22.05
Charbon de bois	0.178	2.02	13.98	150.73

The results show that formulated biofuels emit more CO (2.95 and 2.63 g/MJ) than charcoal ; this is due to the high ash content of biofuels, which tends to smother it during combustion. These results also show that orange and cassava-based biofuels emit less carbon monoxide than charcoal combustion. In addition, the PM2.5 emission factors obtained are close to those of a similar study : 0.08–13.74 g/kg for charcoal stoves and 5.90–11.79 g/kg for traditional biomass stoves [9].

3.4 Economic analysis of biofuel production

The cost of production is assessed on the basis of investment and operating costs (Table 1). It is assumed that the raw material is paid for at €1.53/ton, even though it may be collected free of charge at the start of the project. The evolution of the context for creating added value from agri-food processing by-products is taken into account. It is assumed that the collector collects 20 tons of waste per month. With the average carbonization rate obtained (29–35%), after 7 years, 537.6 metric tons of biofuel are expected at a total cost of €60353, i.e., an average production cost of €0.113/kg. If the raw material is obtained free of charge, the production cost becomes €0.107 per kg of biofuel.

From an energy point of view, the biofuels orange peel and cassava represent (µ= (LHV biofuel) / (LHV charcoal)) 0.70*charcoal and 0.69*charcoal, respectively. The cost of a kilogram of charcoal on the Burkina Faso market averaged €0.177 /kg in 2000, with a maximum of €0.243/kg [14]. With the production costs obtained, we can deduce that biofuels can penetrate the charcoal market and enter consumer habits if other qualities such as hardness, emission factors and their impact on grilled food are taken into account.

4. CONCLUSION

The overall aim of this study was to contribute to the diversification of energy supplies, in particular domestic fuels, from agri-food processing waste. Cassava and orange peels were used as raw materials. Cassava starch (residual material from cassava processing) was used as a binder. The work carried out to achieve the above objectives focused on determining the physicochemical characteristics of the raw materials and biofuels, energy content and emission factors (CO and PM2.5). After drying the raw materials, the carbonization process yielded rates of 29.06% for cassava peels and 34.68% for orange peels. The biofuels formulated are composed of 92% cassava peel powder and 8% cassava starch (L8M92) and 92% orange peel powder and 8% cassava starch (L8M92). Characterization of the formulated biofuels revealed that orange peel biofuels contained 8.88% ash, a fixed carbon content of 36.07%, and an LHV of 21.54 MJ/kg. Cassava peel biofuels contain 19.65% ash and 36.59% fixed carbon, with a PCI of 21.13 MJ/kg. The controlled combustion test (CCT) using the formulated biofuels showed that the CO and PM2.5 emission factors are 22.38 g/kg and 1.38 g/kg, respectively, for the orange peel biofuel and 22.05 g/kg and 1.45 g/kg for the cassava peel biofuel. These results show that cassava- and orange-based biofuels can be used and have CO and PM2.5 emission factors close to those of charcoal. The study enabled us to determine the importance of carbonization and densification on biofuel quality. It also enabled us to assess the impact of its use on the environment. From these results, it should be noted that it is possible to formulate biofuels based on cassava and orange peels. These biofuels have a good energy content with fairly low CO and PM2.5 emission factors, close to those of charcoal. Also, the characteristics of the biofuels formulated are in the same order of magnitude as those in the literature. The use of formulated biofuels in conventional fireplaces also enables good heat transfer (thermal efficiency between 31 and 33%).

Economic analysis has shown that the production cost of biofuels is €0.107 per kg. Notwithstanding the determination of the conditions for consumer adoption, biofuel production as an industrial activity can prosper given the current production and sales costs of charcoal. With a view to improving the performance of biofuels, a follow-up to this research work is recommended. Specifically, it will be relevant to produce other formulas with other types of binders to reduce the ash content of fuels ; to repeat this work using a press adapted for better compaction ; and to produce other formulas by mixing the raw materials used with other more carbon-intensive materials, such as cashew and coconut husks, with a view to improving the energy content of biofuels.

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COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

AUTHORS' CONTRIBUTIONS

Kayaba HARO : Investigation, writing - original draft & editing. Hilary Khatya Pengd-Wende ILBOUDO : Investigation and data curation, Abdoulaye COMPAORE : Investigation and review, Lucman KOALA : Investigation and data curation, Oumar SANOGO : Supervision and methodology validation and paper review."

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