

Gasification of Raw, Roasted and Carbonized Cashew Shells Using and Fixed Bed Co-Current Gasifier

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Abstract

The present study focuses on the improvement of gas quality by gasification of raw and cashew shells heat treatment by roasting and carbonization. The gasifier is a fixed-bed co-current batch mode, with a throat. It has a thermal power of around 30 kW. It meets the need for low electrical power of the order of 10 kWe. It has a double wall with a height of 153 cm and a diameter of 50 cm, and a double air injection. Improving the quality of the gas, consisting of reducing the balsam content contained in the raw shells, as well as the improvement of the physico-chemical characteristics of the shells. And this is done through the roasting and carbonization process. The tests carried out aim to evaluate the energy performance of the gasifier and analyze the gas composition resulting from the gasification of raw, roasted and carbonized cashew shells. The parameters studied are the energy efficiency of the gasifier and the energy capacity of the gas. The study showed that the energy yields of the gasifier by gasification of raw, roasted and carbonized hulls are respectively 47.5%; 28.32% and 31.48%. The specific production rate of the gas is 28.3; 132.76 and 155.32 kg/m²·h respectively for raw, roasted and charred hulls. The gasification times of raw, roasted and charred hulls are 224.33 respectively; 201 and 211 minutes. The composition of syngas shows that the gas produced from cashew shells is low in energy. Indeed, the PCI of gas from the raw, roasted and carbonized hulls is 3.1, respectively; 2.1 and 2.87 MJ/N·m³.

Keywords

Cashew Nuts Shells, Gasification, Roasting, Carbonization, Energy Efficiency

1. Introduction

Agriculture is the main activity of the population of Burkina Faso and represents the main source of income for rural actors. However, this activity generates huge amounts of waste that must be managed; particularly in rural areas. The energy recovery of agricultural residues is therefore important as it strengthens the energy supply. Biomass can help solve the issue of access to modern energy services. Indeed, bioenergy programs contribute to the production of biofuel, heat, steam, syngas and electricity [1]-[3]. The gasification of agricultural residues in some localities in Burkina Faso has made it possible to access electricity. Indeed, gasifier installations in the rice parboiling centers of Dano and Bagre have favored the production of electricity and heat at a given time. However, the majority of gasifiers in operation in Burkina Faso are shut down, for technical reasons and because of the lack of mastery of the technology [4]. The gasification technique is promising as long as the technology is mastered. And this involves either mastering the design and production of the gasifier, but also optimizing the gasification performance. The major difficulty of the gasification technique is the production of high tar and dust in the syngas. This could require treatment of the gas produced before certain applications, particularly in the case of injection into an internal combustion engine. For applications for power generation purposes, gas purification is essential to avoid damage to the engine. This is very expensive in terms of investment, which would lead to an increase in the cost per kilowatt hour (kWh). This is why gasification technology needs to be improved in order to be competitive in the energy market [5]. According to the literature, the co-current fixed-bed gasifier produces less tar compared to other types of gasifiers [6]. This guided the choice of this type of gasifier because it plays an important role in tar production and in the efficiency of the gasification process [7]. The supply of secondary air to the biomass supply of the device is likely to reduce the tar content by 88.7% according to Pan 1999 [8]. Gasification studies on agricultural waste have shown an ability to produce electricity, from the injection of the gas produced in a combustion engine [9]. Indeed, the syngas obtained through the gasification of cashew nut shells can be used in combustion engines for the production of electricity. Shells can be used to produce energy, particularly in the form of heat and electricity, and thus help improve the transformation process and access to electricity in rural areas. In the literature, studies on the thermal energy recovery of cashew hulls such as combustion and gasification have been conducted [10]-[13]. The purpose of this study is to study the operating parameters of the device in order to optimize the energy efficiency of the reactor. To do this, it is necessary to carry out preliminary gasification studies, to analyze the composition of the gas, and to determine the energy performance of the reactor.

2. Materials and Methods

Description of the Experimental Design

The device used is a co-current fixed-bed gasifier with a thermal power of around

30 kW. It meets the need for low electrical power of the order of 10 kWe. It is a double-walled batch gasifier with a height of 153 cm and a diameter of 50 cm. Ash serves as insulation and is located between the two walls of the gasifier. The gasifier adapts to uniform particles and promotes high biomass conversion and the production of clean gas with low tar content. It is used to meet small-scale energy production. The gasifier is subdivided into two parts: a body (reactor) and auxiliary equipment (cyclone, blower and frame). **Figure 1** shows a longitudinal section of the gasifier.

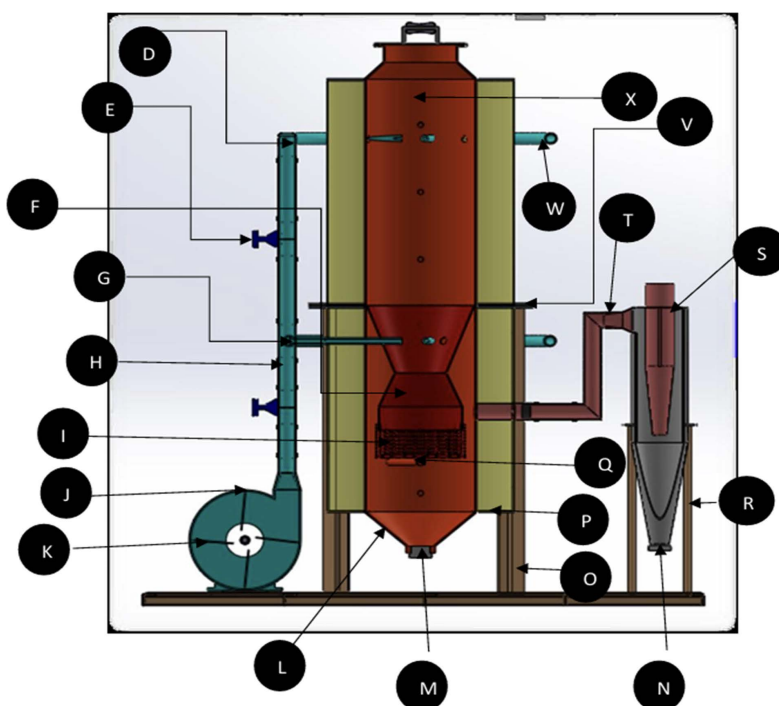


Figure 1. Cross-section of the device.

With:

D: Ring to which the three (3) air supply pipes from the upper section are connected;

E: Valve;

F: Reaction chamber;

G: Air supply hose for lower section;

H: Pipe supplying air to the two (2) rings;

I: Grid;

J: Cover fan blower;

K: Fan propellers of blower;

L: Ash-bin;

M: Ashtray cover;

N: Cyclone cap;

O: Reactor support;

P: Ashtray flange;

- Q: Grid control;
- R: Cyclone support leg;
- S: Cyclone gas outlet pipe;
- T: Pipe linking reactor to cyclone;
- U: Inner cylinder to the lower part;
- V: Main flange;
- W: Ring to which the three (3) hoses feeding the reaction chamber are connected;
- X: Inner cylinder to the higher part.

3. Methods

Four type K thermocouples, with a measuring range of -50°C to $+400^{\circ}\text{C}$ and class 2 accuracy in accordance with standard EN 60584-2, are connected to a data logger to monitor the temperature inside the reactor.

They are located in the drying, pyrolysis, combustion and reduction zones. The ABB EL 3020 gas analyzer is connected to the gasifier to monitor the concentration of the individual components of the gas or vapor, with the exception of explosive mixtures (gas/air or gas/ O_2). The dew point of the test gas is equal to 5°C , below the lowest ambient temperature throughout. The test gas flow rate is between 30 and 60 l/h (+ or -5 l/h). It has 2 sensors (Uras26 and Caldos27) and an O_2 detector. It is switched on 15 minutes before the start of the test. The flow meter is used to evaluate the air flow injected into the gasifier. The value recorded on the volumetric flow meter is noted at the start and end of the test. It allows to measure the air flow rate in volume unit per time unit (l/h, m^3/h , l/min, ...). It is nevertheless possible to correct the volume flow rate values, according to the temperature and/or pressure to deduce the mass flow rate (or in Nm^3/h , Nl/min , ... for gases).

The gasification test is carried out in several stages:

- The ignition stage. In this stage, the agitator is placed in the reactor. Beforehand, 22 kg of cashew shells are weighed. But first, 2 kg of cashew shells are poured into the reactor, mainly into the throat. We then added 1.5 kg of burnt cashew shells to ensure ignition. Then we turn on the blower to send air into the reactor. This takes 5 minutes.
- Filling takes place after the cashew shells ignition stage, with the remaining quantity of pre-weighed cashew shells being poured into the reactor until it is full, of course after the blower has been switched off. The reactor lid is then placed, and water is poured into the top to ensure a watertight seal. A water seal is placed around the cyclone. We then restarted the blower and switched on the data logger to measure the temperature. The agitator is activated every 15 minutes.
- The shutdown is marked by the absence of gas production, after agitation inside the reactor. At the end of the test, the blower is switched off. After recording the data, we shut down the data logger and the gas analyzer. At the end of the test, once the system has cooled down, the cashew shell residues are

weighed. The gasification tests were repeated at least three (3) times for raw cashew shells, as well as cashew shells treated by roasting and carbonization beforehand. The aim was to reduce the balsam that could cause technological problems.

- Temperature data acquisition from real-time recording with the data logger. The data is then recovered using an Excel file.
- The concentration of gas components is read using a computer, in which ABB software is installed. The temperature and gas composition data are then collected on a USB key and processed in an Excel file.
- The recovery of ash and shell residues after gasification enables the energy efficiency of the gasifier to be assessed using the equations below.

Equations Gasifier Energy Performance

The study of gasification performance is possible thanks to work along these lines that we have found in the literature [14]-[16].

The equation used to determine the various gasification parameters is given below:

1) Volume of air

Equation (1) represents the normal volume of air (V_{air}):

$$V_{Nair} = V_{air} \times (T_0/T_a) \quad (1)$$

V_{Nair} is the normal volume of air and ρ_{air} is the density of air at normal temperature *i.e.* 1.292 kg/m³; T_0 and T_a are normal temperature and ambient temperature respectively. The volume of air is obtained from experimental data recorded by the flow meter.

2) Air mass

The mass of air (m_{air}) is calculated using the formula below:

$$m_{air} = \rho_{air}(T_0) \times V_{Nair} \quad (2)$$

With pressure equal to atmospheric pressure, the compressibility factor of gases is close to 1, so the equation of state for perfect gases can be used to calculate the volume of air.

3) Mass of dry gas

The mass of the dry gas (m_{gas}) is calculated from the equation below:

$$m_{gas} = \sum_{i=1}^5 n_i M_i = \frac{V_{gas}}{V_m} \sum_{i=1}^5 [i]_{gas} M_i \quad (3)$$

n_i , M_i , V_{gas} , V_m $[i]_{gas}$, represent respectively the number of moles and the molar mass of component *i* of the gas, the volume of gas, the molar volume at temperature T_m and the molar fraction of component *i* of the gas (CO, CO₂, H₂, CH₄, N₂). The equation of state for perfect gases gives the molar volume (m³/mol) at each temperature (Equation (4)).

$$V_m = \frac{\rho_{N_2}(T_a)[N_2]_{air}}{\rho_{N_2}(T_g)[N_2]_{gaz}} \times V_{air} \quad (4)$$

The total volume of the gases was determined on the basis of the total volume of air, the volume fraction of nitrogen in the gas and the conservation of the mass of nitrogen before and after the reaction (Equation (5)).

$$V_{gaz} = \frac{\rho_{N_2}(T_a)[N_2]_{air}}{\rho_{N_2}(T_g)[N_2]_{gaz}} \times V_{air} \quad (5)$$

$\rho_{N_2}(T_a)$, $\rho_{N_2}(T_g)$, T_a and T_g , represent respectively the density of nitrogen at ambient temperature and at the temperature of gas, ambient temperature, and gas temperature. The density is given by Equation (6) and the volume of the gas by Equation (7).

$$\rho_{N_2}(T) = \frac{M_{N_2}}{V_m} = \frac{M_{N_2} P_a}{RT} \quad (6)$$

$$V_{Ngaz} = V_{gaz} \times \frac{T_0}{T_{gaz}} \quad (7)$$

4) LHV of gas

The LHV of the gas is calculated by acquiring data on the various components that make up the gas produced or syngas (CO, CH₄ and H₂). The gas fractions are measured every second by a gas analyser, and an average of each compound is calculated for the test. In this study, it is expressed in MJ/Nm³.

$$LHV_{gaz} = [CO] \times LHV_{CO} + [H_2] \times LHV_{H_2} + [CH_4] \times LHV_{CH_4} \quad (8)$$

5) Energy efficiency

The energy yield of gasification is given by the ratio of the energy contained in the fuel to the energy contained in the gas produced (Equation (9))

$$\eta_{gaz} = \frac{V_{Ngaz} PCI_{gaz}}{m_b PCI_b} \quad (9)$$

6) Gas production rate

Gas production rate is the volume flow rate of gas produced per unit area of the gasifier grid.

It is expressed using Equation (10):

$$GPR = \frac{V_{Ngas}}{t \times S_g} \quad (10)$$

V_{Ngas} : the normal volume of gas produced during gasification;

S_g : the gasifier grid area;

t : duration of gasification.

7) Specific production rate

Specific gasification rate represents the biomass consumed per hour and per unit area during gasification.

It is expressed in Equation (11).

$$TPS = \frac{m_c}{t \times S_g} \quad (11)$$

m_c : mass of the fuel (raw and pretreated cashew shells).

8) Gas production

Gas production represents the normal volume of gas produced per kg of biomass consumed. It is expressed in Equation (12):

$$P_g = \frac{V_{N_{gas}}}{m_c} \quad (12)$$

9) Thermal power

The thermal power of the reactor is represented by Equation (13) below and is expressed in kW. It is related to biomass energy.

$$P_{th} = \frac{LHV \times m_{biomass}}{t} \quad (13)$$

The volume of gas produced and the mass of biomass consumed are related to the air flow rate injected into the reactor. Under the same operating conditions, TPG , TPS , P_g , P_{th} can be used to compare the performance of gasification using different types of fuel.

4. Results and Discussion

The tests were carried out on a co-current fixed-bed reactor with a throat. Gas composition, mass balances of gasified hulls, ash, tars and air flow rates were measured. Three gasification tests were carried out for each type of biomass (raw shells, roasted shells and carbonized shells). Two air injection rates were set. The first flow rate was set for the half-open valve, and the second for the fully-open valve. The aim of the study was to evaluate the energy performance of reactor and the impact of cashew shell heat treatment.

4.1. Chemical Formulas of Cashew Shells

The general formula of biomass is $CH_yO_xN_z$. The chemical formulas of cashew shells were determined from the elemental analysis of the shells. They are mentioned in **Table 1**.

Table 1. Chemical formulas of cashew shells.

Chemical formulas	C	H (y)	O (x)	N (z)
Raw shells	1	1.43	0.48	0.01
Roasted shells	1	1.55	0.46	0.01
Carbonized shells	1	1.33	0.4	0.01

4.2. Gasifier Efficiency

Table 2 shows the energy performance of the gasifier.

ER of roasted shells is higher than that of ER of raw and carbonized shells. This means that the PCI of the synthesis gas is the lowest [17]. And that the gasification of carbonized shells generates more tar than raw and roasted shells.

Table 2. Energy performance parameters of the gasifier.

	Mass consumed (kg)	Biomass mass/real air mass	ER	Volume of air (m ³)
Raw shells	6.69 ± 0.09	0.19 ± 0.04	0.33 ± 0.03	25.73 ± 0.30
Roasted shells	6.87 ± 0.11	0.27 ± 0.03	0.43 ± 0.01	22.15 ± 0.4
Carbonized shells	7.50 ± 0.03	0.27 ± 0.02	0.29 ± 0.02	21.55 ± 0.34

4.3. Gas Composition

Table 3 shows the gas composition.

Table 3. Composition de gaz.

	CO (%)	CO ₂ (%)	CH ₄ (%)	H ₂ (%)
Raw shells	13.5 ± 0.06	10.1 ± 0.04	1.8 ± 0.05	7.1 ± 0.19
Roasted shells	10.5 ± 0.9	7.8 ± 1.6	0.8 ± 0.6	4.7 ± 1.5
Carbonized shells	14.9 ± 0.9	8.8 ± 1.4	0.8 ± 0.08	5.4 ± 0.3

The results in **Table 3** show the gas composition of the different biomasses. The results in **Table 3** show the gas composition of the different biomasses. The CO₂ of the raw Shells is higher than that of the pre-treatment hulls. This means that the oxygen supply during the gasification process is high, which reduces the quality of the syngas [17]. The heat treatment of cashew shells resulted in the reduction of H₂ and CH₄ in the syngas. The production of CO in the gas is improved with the treatment of the biomass by carbonization unlike roasting. This is proven by the studies conducted by Moreira and. *et al.* 2017, which showed through the analysis of the gas phase, that the temperature influences the composition of the syngas with different H₂:CO ratios under nitrogen and air flows [18]. The CH₄ content remains below 2%, this indicates that the tar rate is low in the gas. Indeed, the tars and CH₄ come from the pyrolysis gases, so the presence of CH₄ in the output gas is explained by the fact that the oxidation step is not complete and there are still hydrocarbons in the syngas [19]. Also, the pretreatment allowed to have CH₄ rates below 1%, which means that the tar in the syngas will be reduced. We were able to observe a low release of smoke at the time of gasification of the pretreated hulls compared to the raw hulls. This was proven in a study conducted by Amaliyah *et al.* [20].

Table 4. Gas production volume and duration balance.

	Volume of gas (m ³)	Normal Volume of gas (Nm ³)	Time of gasification (mn)
Raw shells	42.55 ± 0.67	24.26 ± 1.72	224.33 ± 0.01
Roasted shells	31.52 ± 0.69	20.47 ± 0.45	201.00 ± 1
Carbonized shells	37.19 ± 0.3	21.08 ± 1.68	211.00 ± 1.66

In **Table 4**, gas production and gasification time decreased with heat treatment. This means that the gasification of heat treatment shells is faster than that of raw shells as revealed in the study of Ibrahim *et al.* 2018 [3]. On the one hand, this is probably due to the reduction of volatile matter following roasting and carbonization. On the other hand, we know that balsam has an LHV of around 36 MJ/kg according to Sanger *et al.* 2011. Tagutchu *et al.* 2012 carried out studies on the behaviour of balsam from the roasting and pyrolysis of hulls. More specifically, they conducted flammability tests on balsam extracted from roasted and charred husks. And they showed that the pyrolysis balsam ignites more easily after pre-heating and burns for a long time, testifying to its low flash point. Balsam has an LHV of around 36 MJ/kg according to Sanger and. *et al.* [21]. Tagutchou *et al.* [22] carried out studies on the behaviour of balsam from the roasting and pyrolysis of hulls. More specifically, they conducted flammability tests on balsam extracted from roasted and carbonized cashew shells. And they showed that the pyrolysis balsam ignites more easily after pre-heating and burns for a long time, testifying to its low flash point. They also showed that balsam extracted from roasted and carbonized cashew shells are highly volatile at a temperature of 105°C [22]. This means that the balsam influences the combustion phase during gasification. The balsam from the heat-treated hulls does not affect the combustion phase, because balsam of heat treatment emits enough vapour to form, with the injected air, a gaseous mixture that ignites under the effect of heat, but not enough for combustion to sustain itself. This explains why gasification of raw shells lasts longer and produces more gas.

Table 5 shows the energy performance of the gasifier.

Table 5. Energy performance parameters of the gasifier.

	LHV gas (MJ/Nm ³)	Gas production yield (%)	Gas Production (Nm ³ /kg)	Thermic power (kW)	Gas production rate (Nm ³ /m ² ·h)	Specific production rate (kg/m ² /h)	Gas temperature (K)
Raw shells	3.1	45.11	3.63	12.39	1160.97	320.15	476.39
Roasted shells	2.1	24.64	2.98	14.46	1093.30	349.54	377.26
Carbonized shells	2.87	30.95	2.81	15.44	1072.52	381.59	458.08

Gasification of roasted biomass under severe conditions leads to a decrease in gas LHV and yield compared to raw biomass [23]. The LHV of the gas varies little with the heat treatment of cashew shells, according to Bénéwindé *et al.* [24], reducing the balsam of raw hulls has a small impact on the LHV of the hulls. The production yield of raw cockles in the present study is close to that found by Alcócer *et al.*, which is 50.4% [25]. Heat treatment of cashew shells by roasting and carbonization reduced the gasification yield of the hulls. The specific production rate of raw and heat treated cashew shells tends towards those found in the literature [10] [25]. Heat treatment of cashew shells has led to an improvement in the specific gas production.

The thermal power of the gasifier is improved with pre-treatment. Pre-treatment of the hulls reduced volatile matter, thus limiting the production of balsam during gasification, and solved the problem of obstruction of the gasifier ducts. This resulted in a significant release of synthesis gas. As the raw husks were torrefied and carbonised at 250°C and 300°C respectively, the temperature of the gas produced was affected, as the gas temperature dropped with the pre-treatment. In the literature, it has been shown that the volatile matter content, and fixed carbone rate are reduced with pretreatment by roasting and carbonization [24] [26] [27]. This justifies the reduction in gas yield from the hulls, which drops from 45.11% for raw hulls to 24.64% and 30.95% for roasted and carbonized hulls respectively.

The gasification of raw shells is slow compared to that of roasted and carbonized shells. Values of 320.15 kg/m²·h, 349.54 kg/m²·h and 381.59 kg/m²·h of specific rate production (TPS) were obtained respectively for raw, roasted and carbonized shells. Indeed for this type of reactor, Kaupp and Goss, 1981, cited by Mohammad Kamruzzaman *et al.* [28]; places a minimum specific consumption of 509 kg/m²·h. The low biomass consumption and specific consumption are probably due to a low air supply, hence the need to review the fan power as well as the air supply system of the gasifier by increasing the thickness of the air flow pipes especially at the oxidation zone.

The main consequence of increasing the LHV is the increase in the thermal power of the reactor when there is pretreatment. Thermal powers of 12.39 kW; 14.46 kW and 15.44 kW of the reactor were obtained during the gasification of raw, roasted and carbonized shells respectively. The improve of reactor performance, the improvement in the reactor's performance is due to low or almost non-existent release of balsam during the gasification of heat-treated hulls not only limits hull packing, but also the obstruction of gas flow channels. This is because, during gasification, the released balsam flows towards the cold zones of the gasifier. This state allows air to circulate easily between the husks, and limits obstruction of the gas flow channels.

A low biomass consumption rate obtained for the gasification of pretreated shells compared to raw shells was observed. The results obtained are similar to those of Ibrahim *et al.*, 2018 [3]. The fuel consumption could be optimized from additional studies. However, it is essential to improve the gasification process by increasing the injected air flow, possibly from a mixture of air and water vapor injection. This is a perspective that will be considered in future studies with the gasifier.

5. Conclusion

The gasification of cashew nut shells abandoned by processing units is useful for heat and electricity applications. But for electricity production, it is essential to produce a clean, high-quality gas. In this study, we carried out an evaluation of the energy efficiency of the gasifier and the energy capacity of the gas. The study objective of gasification of raw, roasted and carbonized shells is to produce a clean

quality gas for power generation applications. A fixed bed gasifier in batch mode of co-current type was realized and tested in this study. The results showed that gas LHV of cashew shells are 3.1 MJ/Nm³, 2.1 MJ/Nm³ and 2.7 MJ/Nm³ respectively for raw, roasted and carbonized shells. The thermic power of raw, roasted and carbonized shells is improved due to the reduction of the baume and the fluidity of the injected air flow. It is defined respectively at 12.39 kW; 14.46 kW and 15.44 kW, also, evolving biomass consumptions of the order of 320.15 kg/m²·h; 349.54 kg/m²·h and 381.59 kg/m²·h respectively during the gasification of raw, roasted and carbonized cashew shells. This is due to the fact that the reduction of the baume limits the obstruction of the ducts during gasification. The gas temperature at the outlet of the gasifier decreases depending on the type of biomass. This is due to the fact that the pretreated shells have undergone heat treatment before the gasification process. The pretreatment of cashew shells still reduces the gas production. The study of the gasification of raw and heat-treated hulls shows that the quality of the gas is improved, as is the energy performance of hull gasification. However, the LHV of the gas from pre-treated hulls is not improved by torrefaction and carbonisation of the hulls.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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