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Gasification of charcoal derived from tropical wood residues in an updraft fixed bed reactor

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ABSTRACT

This paper aims to produce hydrogen-rich synthesis gas from the charcoal of three tropical tree species. The approach involves sequentially the production and characterization of charcoal, the production of syngas by air gasification; and then the determination of the composition of syngas. Proximal analysis of charcoal gave ranging from 6.10 to 7.05 %; 71.51 to 77.50 %; 20.14 % to 26 % and 1.83 % to 2.48 % respectively for moisture contents, fixed carbon, volatile matter and ash contents. The gas proportions of the syngas for the three wood species do not vary significantly, with hydrogen content ranging from 20.98 % to 21.88 %, carbon monoxide (CO) from 22.2 % to 23.29 %, H_2/CO ratios between 0.91 and 0.98, and the calorific value of the syngas around 6.21 MJ/Nm^3. The above results show that the wood residue charcoals of the three species used in this study are suitable for the production of hydrogen-rich syngas.

1. Introduction

Over the past two decades, energy demand around the world has been significantly growing, which has resulted an increase in greenhouse gas emissions (Ahmad and Zhang, 2020). Excessive consumption of fossil fuels has led to a decrease in energy supply and contributes to many environmental issues (Xu et al., 2020). Hydrogen is one of the important energy vectors for obtaining high value-added products such as urea, fuel, and methanol (Alnouss et al., 2020), yet 98 % of the hydrogen currently in use is produced from fossil sources, against only 2 % from renewable sources (Lepage et al., 2021). There is a need to explore, investigate, and further improve processes for the production of clean hydrogen. Countries around the world are intensifying efforts to develop renewable energy resources such as agricultural biomass, energy grasses, and wood processing residues that have attractive characteristics for energy generation (Epesse Misse et al., 2020).

Cameroon has a large variety of biomass: woody biomass, agricultural residues, animal manure and municipal solid waste (Bot et al., 2022; Mboumboue and Njomo, 2018). Wood processing residues (woody biomass) have a zero CO_2 balance (Schubert and Blasch, 2010), representing a reliable energy alternative to fossil fuels (Nzotcha and Kenfack, 2019). In Sub-Saharan Africa, Cameroon has the third largest biomass potential, with 40 % of its area (about 22 million hectares) covered by forests, 79 % is exploitable for wood. The most exploited wood species in Cameroon are: Ayous (37.2 %), Sapelli (18.9 %), Azobe (6.6 %), Tali (5.7 %), Movingui (2.0 %), Moabi (1.8 %), Padouk (1.3 %) and others (26.5 %) (Saha Tchinda et al., 2018), which produce a huge amount of residues that are often eliminated irresponsibly (Sessa et al., 2021). Movingui (*Distemonanthus benthamianus*), Padouk (*Pterocarpus soyauxii*) and Fraké (*Terminalia superba*) are species found in African tropical forests (Yu et al., 2022). In Cameroon, they are crucial to the timber trade and are found in abundance in the forests of the East, Littoral, Centre and South regions; they are the most highly prized species and are of major interest to timber companies and research (Lissouck et al., 2018; Yu et al., 2022). The exploitation of these forest species generates large quantities of residues that constitute an interesting energy resource (1.2 million tonnes of wood waste in 2006 in Cameroon) (Saha Tchinda et al., 2018). The production of syngas through gasification seems to be a promising way to valorise these forest residues. It is also one of the most promising ways to combat the current

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climate change (Morya et al., 2022).

Gasification is a thermochemical process through which a carbon-based fuel is converted into a fuel gas in a gasifier (Ma et al., 2019). It is carried out in the presence of gases such as air, pure oxygen, water steam, carbon dioxide, nitrogen or a mixture of these to produce a syngas with a specific composition (Lui et al., 2020). Air and oxygen are used as gasification agents for their high oxidising power (high carbon conversion) and low cost, while steam is used to increase the hydrogen content of the syngas (Maisano et al., 2019).

Several research studies carried out the importance of recovery forest biomass, gasification process using various biomasses and characterization of syngas. Nwachukwu et al. (2021) studied the impact of forest biomass on CO_2 emissions from the Swedish steel industry. The results showed that the efficient use of forest biomass in steelmaking technologies could help reduce their emissions by 43 %. This demonstrates the important role that forest biomass can play in reducing CO_2 emissions. Chen et al. (2013) compared the gasification performance of raw biomass, torrefied biomass and coal. The results show that the content of CO and H_2 in the gas is highest for coal, followed by torrefied biomass and lowest for raw biomass. They also specify that torrefied and carbonised biomass (charcoal) has better energy and proximal properties than raw biomass. Yoon and Lee (2012) used bituminous coal, eco-coal, and oak charcoal as gasification feedstocks and the syngas with the best H_2/CO ratio was obtained from oak charcoal. Galindo et al. (2014) studied the influence of gasification parameters of on the quality of eucalyptus wood the gas produced using a double stage downdraft gasifier with air as the agent. They noted that with a single-stage air supply, the temperatures of the pyrolysis and reduction zones depend on the heat released from the zone where air is supplied. Hu et al. (2015) gasified municipal solid waste and pointed out that the high moisture content of biomass favours CO_2 production, CH_4 and CO decrease. In addition, the additional steam in the reactor created by the moisture of the biomass causes the temperature to drop and consequently decreases the amount of gas produced. Marcantonio et al. (2019) made the same observation by varying the steam rate in the gasifier. Rinaldini et al. (2017) gasified a mixture of poplar and pine wood chips, and the syngas produced simultaneously powers a combustion engine with diesel fuel. The syngas successfully replaced 60 % of the diesel fuel and the engine showed good performance being fuelled with syngas. Aydin et al. (2019) performed air gasification of wood pellets in a downdraft gasifier and the result show that the proportions of CO and H_2 increased with the gasification temperature; the characteristics of the biomass (density, porosity, size) influence the operating parameters of the reactor. Liao et al. (2019) used pine sawdust collected from a furniture factory as a gasification feedstock and stated that tar is the major problem in gasification. Zeng et al. (2014) pointed out that the two-stage gasification is efficient for the removal of tars in the gasifier at moderate temperatures and also that this technique is very suitable for the production of combustible gas. Nzali et al. (2019) studied the influence of particle size on the gasification of Ayous sawdust in a batch reactor and the results showed that the size significantly influences the reaction time, the temperature as well as the syngas production. Lu et al. (2018) make the same observation as Nzali et al. by gasifying the carbonised woody briquettes in a updraft fixed bed gasifier. Nwokolo et al. (2020) air gasified eucalyptus and the gas was composed of 22.3 to 22.5 % H_2, 22.3 to 24.3 % CO, 41.5 to 42.9 % N_2 and they indicated that the high concentration of nitrogen in the syngas is attributed to the main nitrogen component of air. Veeyee et al. (2021) investigated by thermodynamic modelling the suitability of sawdust processed in a factory in Cameroon for electricity generation through syngas. The results indicated that the energy requirements of the said factory of about 3.3 MW/week can be met by the gasification of its own generated waste. Lepage et al. (2021) reported that air gasification can produce syngas with a mean hydrogen content of 15 % and a H_2/CO ratio of 0.75.

In the light of the literature provided to date, it appears that several wood species with a chemical composition favourable to the production of syngas have been the subject of experiments, namely Pine, Oak, Poplar, Eucalyptus and Ayous. However, to the best of authors' knowledge, other tropical species such as Padouk, Movingui and Frake have not been studied for gasification, even though they have a favourable chemical composition and they are of interest to the wood research and industry in Cameroon. This paper investigates the possibility of producing syngas from the charcoal of Padouk, Movingui and Frake residues by gasification. Also, according to the literature available, non-carbonised biomasses are mainly used for gasification, yet they have high volatile matter content, moisture content and low fixed carbon and energy density compared to charcoal. In order to reduce the volatile content and maximise the fixed carbon content and energy density of the feedstock, the present study is conducted in two distinct steps: The producing charcoal from the three selected forest residues, conducting the physical, proximal, and ultimate characterization of said charcoal; then producing the synthesis gas, analysing the gasification temperature as a function of the particle size, and finally, determining the composition of the syngas and heat values. This approach facilitates the primary cracking of the tar and thus reduces the tar content in the syngas at the gasifier outlet. The importance of the present study is that it proposes a means of utilising the residues from wood processing activities to promote energy development.

2. Charcoal production

2.1. Raw materials

The raw materials are residues from the exploitation of three tropical wood species, namely Padouk, Movingui and Frake, which were collected in Douala (Movingui, Padouk) and Yaoundé (Frake) from January to March 2022.

2.2. Initial chemical composition of the wood species

The chemical characterization of wood species was performed in order to determine lignin, cellulose and hemicellulose content according to Badu et al. (2011), Kapoor et al. (2015), and Sluiter et al. (2004). For lignin determination, 14 ml of cold 72 % sulfuric acid was added to 1 g of the extractives free sample and mixed. The mixture was allowed to sit for 2 h. After 2 h, the mixture was washed and diluted to 3 % sulfuric acid in a 1 l conical flask. The mixture was then boiled for 4 h on high heat. The insoluble material was filtered once it had settled. The residue was cleaned and dried in an oven at 105 degrees Celsius for 2 h before being cooled and weighed as the lignin content (Badu et al., 2011; Sluiter et al., 2004).

For cellulose determination, 2 g of the extractive free sample was placed in a 250 ml beaker, 100 ml of 17.5 % NaOH solution was added, and the mixture was agitated at 25C for 30 min. After filtering the contents of the beaker, it was washed with 25 ml of 9.5 % NaOH solution and 20 ml sections of 100 ml pure water. The residue was washed again with distilled water and 40 mL of 10 % acetic acid, followed by 1 l of distilled water. The residue was then dried for 24 h at 105 °C to achieve a constant weight (Badu et al., 2011).

The holocellulose percentage (cellulose + hemicellulose) was determined as described by Setter et al. (2020), 180 ml distilled water, 8.6 g sodium chloride, 6.0 ml of ethanoic acid, and 6.6 g sodium chloride were added to 2 g of the extractive free sample. The mixture was then digested for 3 h in a 250 ml conical flask at 70 °C under reflux. It was then allowed to cool before being filtered and washed with five 20 ml portions of 100 ml of distilled water. The residue was then dried at 105 °C for 24 h to achieve a constant weight (Badu et al., 2011). Hemicellulose contents were calculated from the difference between holocellulose and cellulose values (Setter et al., 2020).

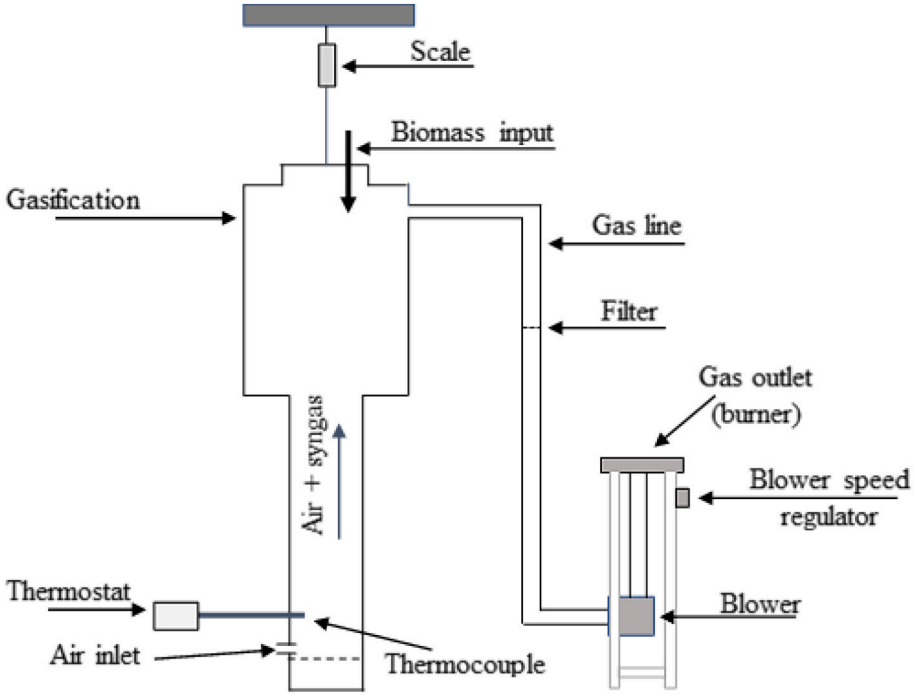

Fig. 1. Simplified diagram of the experimental setup.

2.3. Carbonisation process

The charcoal was produced by the carbonisation in a traditional kiln as described by Freddy et al. (2022). The wood residues have been naturally dried beforehand. The wood bed is formed on a flat surface and covered with grass and soil to improve thermal insulation and allow better heat retention in the kiln. After ignition, the furnace is checked regularly to ensure that the carbonisation process is going well and to guarantee good quality charcoal at the end of the process.

3. Characterization of wood charcoal

3.1. Proximal analysis

3.1.1. Moisture content

Moisture content is the amount of water remaining after drying of a material and is expressed as a percentage of dry weight. It was determined according to the NF EN 14774 standard. The technique consisted of using a model HC311 balance with an accuracy of 0.01 g to weigh the coal samples (wet mass W_h), introducing them into a model 101-1AS oven heated to 105 °C for 48 h, and then weighing again to obtain the dry mass (W_0). As in the study by Mfomo et al. (2020), the moisture content (MC) is determined on the basis of the dry mass by the following Eq. (1).

$$MC = \frac{W_h - W_o}{W_o} \times 100 \quad (1)$$

3.1.2. Volatile matter

Volatiles are compounds that can escape from the solid matrix into the gaseous state very quickly when the fuel is subjected to a high temperature under an inert atmosphere (Mfomo et al., 2020). The volatile content was determined by following the experimental protocol described by Abidemi et al. (2022). The muffle furnace had been preheated to 900 °C. The procedure consists of measuring the mass of a sample of charcoal powder, placing it in a crucible and then in the furnace (inert atmosphere) for 7 min, and finally measuring the mass of the crucible + sample. The calculation of the volatile matter content is done using the following formula:

$$VM = \frac{M_2 - M_3}{M_2 - M_1} \times 100 \quad (2)$$

where VM is the volatile matter content, M_1 is the mass of the empty crucible, M_2 is the mass of the crucible + sample and M_3 is the mass after preparation.

3.1.3. Ash content

The ash content is the percentage by mass of ash produced for a fuel (Mfomo et al., 2020), it was determined with a slight modification of the protocol described by Ajimotokan et al. (2019). A muffle furnace and ceramic crucibles are used; 2 g of crushed and sieved charcoal sample is introduced into the furnace for 3 h at a temperature of 815 °C. The mass of ash (M_a) produced after complete carbonisation of the sample is measured. The ash content is calculated by the following Eq. (3):

$$AC = \frac{M_a}{M_c} \times 100 \quad (3)$$

where AC is the ash content, M_c is the mass of the charcoal sample, and M_a is the mass of ash produced after 3 h of carbonisation.

3.1.4. Fixed carbon

The fixed carbon rate is the carbon remaining after the removal of volatile matter and ash from the anhydrous solid fuel (Ajimotokan et al., 2019). It is obtained from the results of previous tests and is calculated using the following Eq. (4) (Samadi et al., 2020):

$$FC = 100 - (VM + AC) \quad (4)$$

3.2. Ultimate analysis of charcoal

The elemental composition was carried out as recommended by Epesse Misse et al. (2020) using an automated elemental analyzer (EuroVector EA-3000) and in accordance with ISO 29541 (2010). The contents of Carbon, Hydrogen and Nitrogen were measured, and the oxygen concentration was calculated based on the total mass balance

Table 1
Chemical composition of the three wood species.

	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Reference
Frake	46.1 ± 0.7 46.64	17.1 ± 0.5 16.29	30 ± 0.8 31.17	This study (Badu et al., 2011)
Movingui	37.7 ± 0.5 37.0	12.8 ± 0.4 12.5	28 ± 0.6 27.0	This study (Misse et al., 2018)
Padouk	40.8 ± 0.4 41.9	11.1 ± 0.3 11.0	29 ± 0.5 30.6	This study (Misse et al., 2018)

according to ASTM 3176-09 (2009) standard.

The H/C and O/C atomic ratios are indices of the intensity of carbonisation and express the degree of thermal alteration of coal. They were calculated according to the following Van Krevelen formulae (Epesse Misse et al., 2020):

$$H/C = \frac{\frac{\%H}{1}/N}{\frac{\%C}{12}/N} \quad (5)$$

$$O/C = \frac{\frac{\%O}{16}/N}{\frac{\%C}{12}/N} \quad (6)$$

where %C, %H, %O are the percentages of carbon, hydrogen and oxygen respectively and N is the Avogadro number ($N = 6.02 \times 10^{23}$ atoms/mol).

3.3. Determination of the Higher Heating Value

The Higher Heating Value (HHV) indicates the amount of thermal energy released when charcoal is burned (Bot et al., 2021). It was determined according to ASTM 5865, 2012 as described by Joseph et al. (2020). using an oxygen calorimeter bomb model XRY-1A+ with a precision of 0.001 K and a balance model HC311 with a 0.01 g precision. A sample of 1 g was taken from those used for the moisture content determination and used for the determination of the Higher Heating Value (HHV).

4. Gasification process

4.1. Experimental setup

The experimental gasification set-up represented by the simplified diagram in Fig. 1 is a updraft fixed bed gasifier. Air was chosen as the gasification agent due to its ease of implementation in the study conducted. The gasification reactor has a total height of one meter (1 m) and consists of two parts with different diameters. The upper part is 0.35 m high and 0.25 m in diameter. The lower part is 0.6 m in height, with a diameter reduced to 0.1 m to increase the concentration of the raw material. The whole system is closed with a PVC cover of 0.125 m in diameter. The system is internally heated (autothermal), and the feedstock is ignited directly through the air inlet (located 0.1 m from the bottom of the reactor). The hot gas produced in the reduction zone gradually cools down through the relatively low-temperature combustion and drying zones and exits through a pipe attached to the reactor and connected to a burner. A blower model BFB1012EH with the characteristics of 12 V power and 2.94 A current, including an operating speed control device, was used to supply the gasifier with air by suction. The air and product gas conducting pipes have a filter that retains any particles contained in the air or in the syngas.

4.2. Sampling

The raw material used for gasification is charcoal from the carbonisation of Movingui, Padouk and Frake residues. The best particle size for non-catalytic gasification was between 0.15 and 51 mm, and taking into account the specific design of the gasifier, three particle sizes of charcoal were selected: $d \leq 5$ mm, $5 < d \leq 10$ mm and $10 < d \leq 15$ mm.

4.3. Experimental approach

The non-catalytic gasification experiment of Frake, Movingui and Padouk charcoal was carried out at room temperature using three particle sizes. Due to the reactor design, charcoal with a mass of 3000 g is introduced into the gasification reactor at the beginning of the experiment. The blower is set to full power to ensure a constant air flow, and the reactor is switched on. The temperature in the reduction zone is monitored instantly using a K-type thermocouple connected to a model C700FD00-M*AN thermostat. The mass of the gasifier and feedstock assembly is controlled using a digital balance model, OCS-L. The gas produced is ignited during each experiment to confirm that it is syngas. The gasification process takes 60 min, and the remaining feedstock is weighed with a 0.01 g precision balance. The experiments were carried out three times for each size of charcoal. In this study, the reactions are autothermal, and the air flow rate and atmospheric parameters are assumed to be constant throughout the experiment.

4.4. Determination of syngas composition and heating value

According to Cerone et al. (2020), the syngas mainly contains hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), and dinitrogen (N_2) in the case of air or enriched air as gasification medium. The composition was analysed using.

Gas Chromatography (GC) on an HP 6890 fitted with a Thermal Conductivity Detector (TCD).

The Low Heating Value (LHV) and Higher Heating Value (HHV) of the syngas produced were calculated using two mathematical models. The first one was developed for LHV calculation by Maisano et al. basing on the composition of the syngas (Maisano et al., 2019) (Eq. (7)). The second one performed for HHV calculation was reported by Ma et al. (2019) (Eq. (8)).

$$LHV_{syngas}\left(MJ/Nm^3\right) = \left(10.7 \times \%H_2 + 12.636 \times \%CO + 35.82 \times \%CH_4\right)/100 \quad (7)$$

$$\mathrm{HHV_{syngas}}\left(\mathrm{MJ/Nm^3}\right) = \left(12.75 \times \%H_2 + 12.63 \times \%CO + 39.82 \times \%CH_4\right)/100 \quad (8)$$

4.5. Validation of the gasification experiments

The gasification experiments were carried out three times for each particle size. For each size, the mean was calculated and the standard deviation between the results was determined, expressed in percentage and named relative error. Experiments are considered valid if the relative error is <10 % (Nzali et al., 2019). Table 6 in Section 5.3.5 shows the relative errors obtained in the experimental phase.

5. Results and discussion

5.1. Chemical composition of the wood species

Knowing the chemical properties of a certain lignocellulosic material is a key step toward its use as a fuel. Table 1 reveals the chemical compositions of wood species investigated in this study and data from literature.

Frake is composed of cellulose (46.1 ± 0.7 %), hemicellulose (17.1 ± 0.5 %) and lignin (30 ± 0.8 %); Movingui contains cellulose (37.7 ±

Table 2
Proximal characteristics and Higher Heating Value of charcoal.

Biomass	Proximal characteristics				HHV (MJ/kg)	References
	MC (%)	FC (%)	VM (%)	AC (%)		
Frake charcoal	6.17 ± 1.66	71.51	26 ± 0.81	2.48 ± 0.23	28.73 ± 0.8	This study
Movingui charcoal	6.68 ± 0.8	72.76	25.41 ± 0.76	1.83 ± 0.24	29.21 ± 0.51	
Padouk charcoal	7.05 ± 0.8	77.5	20 ± 1.63	2.33 ± 0.23	32.77 ± 1.07	
Wood charcoal	<10	75 à 80	20 à 25	3 à 4	–	(FAO, 1985)
Frake charcoal	7.47 ± 0.63	58.39 ± 3.79	30.54 ± 3.84	3.58 ± 0.93	26.62 ± 3.52	(Mfomo et al., 2020)
Movingui charcoal	5.40 ± 0.65	70.97 ± 2.00	22.50 ± 3.00	2.07 ± 0.55	28.99 ± 0.49	
Oak charcoal	0.6	70.37	27.61	1.42	30.312	(Yoon and Lee, 2012)

MC = Moisture Content; FC = Fixed Carbon; VM = Volatile Matter; AC = Ash Content, HHV = Higher Heating Value.

Table 3
Ultimate analysis and atomic ratio of wood charcoal.

Biomass	Ultimate analysis						
	C (%)	H (%)	N (%)	O (%)	H/C	O/C	References
Frake charcoal	47.3 ± 0.35	5.3 ± 0.35	0.37 ± 0.08	47.03	1.25	0.71	This study
Movingui charcoal	48.1 ± 0.48	5.11 ± 0.4	0.29 ± 0.07	46.5	1.27	0.70	
Padouk charcoal	49.16 ± 0.32	5.7 ± 0.21	0.38 ± 0.09	44.76	1.28	0.69	
Beech sawdust	50.3	5.3	0	44.4	–	–	(Couhert et al., 2009)
Movingui sawdust	49.3	5.2	0.3	45.2	1.27	0.69	(Epesse Misse et al., 2020)
Padouk sawdust	49.6	5.3	0.3	44.8	1.28	0.68	
Pine particles	50.54	7.08	0.15	41.11	–	–	(Niu et al., 2017)

C = Carbon; H = Hydrogen; N = Nitrogen; O = Oxygen.

0.5 %), hemicellulose (12.8 ± 0.4 %) and lignin (28 ± 0.6 %) and Padouk is composed cellulose (40.8 ± 0.4 %), hemicellulose (11.1 ± 0.3 %) and lignin (29 ± 0.5 %). These values are close to literature findings according to Badu et al. (2011) and Epesse et al. (2018). Such chemical elements play a significant role in the pyrolysis process (Setter et al., 2020). Like most tropical forest biomass, the wood species studied have relatively high cellulose values. A high (hemicellulose + cellulose)/lignin ratio produces a large amount of syngas and a high cellulose content favours hydrogen production (Lepage et al., 2021). The cellulose and hemicellulose contents of the three species show that they are suitable for syngas production, as does Ayous (46.5 % cellulose, 16.2 % hemicellulose, 16.2 % lignin) which was gasified previously (Nzali et al., 2019).

5.2. Characteristics of wood charcoal

5.2.1. Results of proximal analysis and Higher Heating Value

The results of the proximal analysis and Higher Heating Value of the three charcoals of different species used in this study are presented in Table 2 below, along with some data from the literature for comparison purposes.

The moisture contents obtained in this study were 6.17 %, 6.68 % and 7.05 % for Frake, Movingui and Padouk charcoal, respectively. These values are lower than the 10 % acceptable for good quality charcoal. As the moisture content of the biomass is an important parameter for gasification, it must be low to produce good quality syngas. Although increasing the moisture content of biomass increases the H_2 content in the syngas due to the water gas shift reaction, it also increases the content of undesirable elements such as CO_2 and decreases the CO content (Plis and Wilk, 2011). Thus, with low moisture contents (6.17 % to 7.05 %), the charcoal in this study can produce syngas with low levels of undesirable elements.

The volatile matter values obtained in this work for Frake, Movingui and Padouk charcoal are 26 %, 25.41 % and 20.14 % respectively. These results show that Frake has a higher volatile matter content than Movingui and Padouk. This implies that light woods (low density) produce charcoal with high ash content while heavy woods (high density) give charcoal with reduced volatile matter content. This is consistent with the results of Joseph et al. (2020) presented in Table 2. The volatile matter content of the biomass influences the gasification products. Thus, an increase in the volatile matter content of the biomass leads to a decrease in the H_2 content and the H_2/CO molar ratio in the syngas.

The values for ash content are 2.48 % for Frake, 1.83 % for Movingui and 2.33 % for Padouk. These values are close to those of (Mfomo et al., 2020) presented in Table 2. High ash content in the gasification feedstock would decrease the CO content of the gas and increase its H_2 content while having no influence on the CO_2 composition. From the above, it can be seen that the low ash content of the charcoals produced will allow the production of syngas with low CO and CO_2.

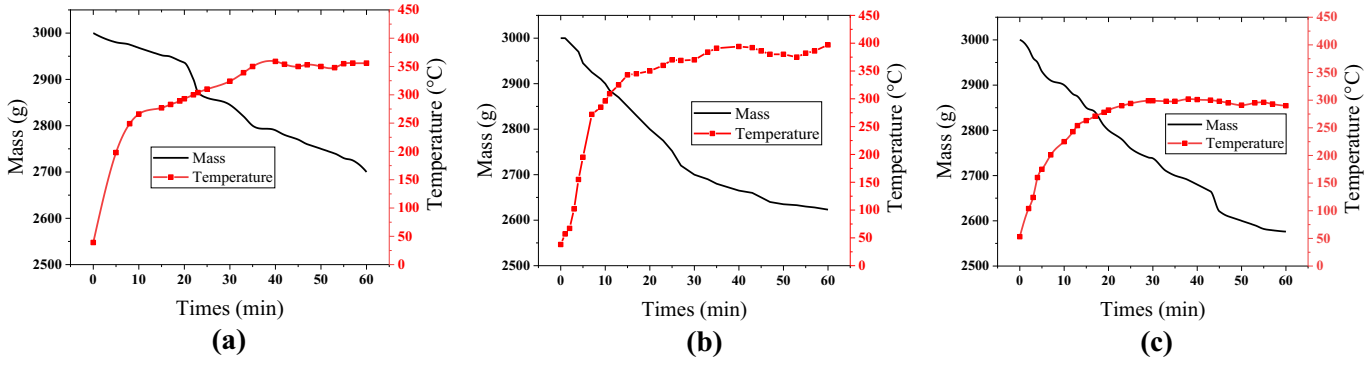

Fig. 2. Loss and temperature profile of charcoal: (a) Frake, (b) Movingui, (c) Padouk (d ≤ 5 mm).

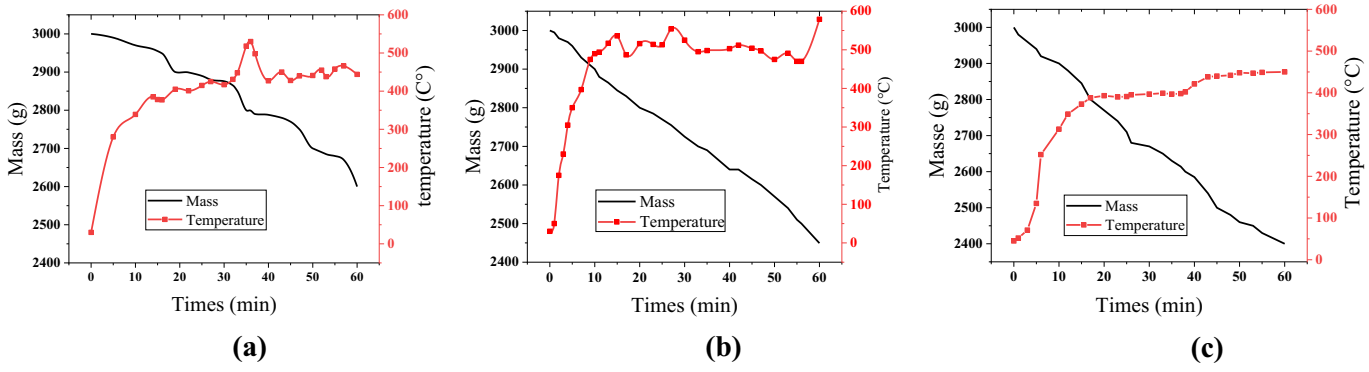

Fig. 3. Mass loss and temperature profile of charcoals: (a) Frake, (b) Movingui, (c) Padouk (5 < d ≤ 10 mm).

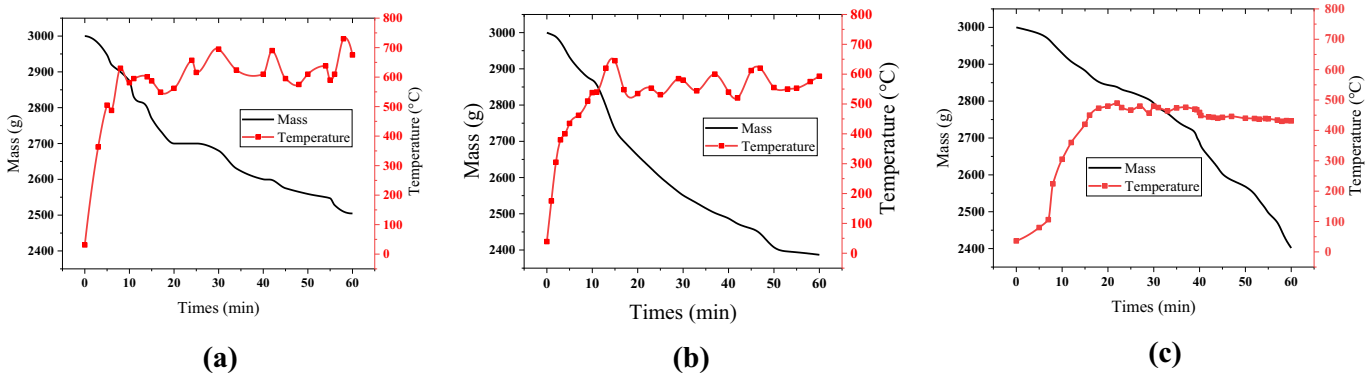

Fig. 4. Mass loss and temperature profile of charcoal: (a) Frake, (b) Movingui, (c) Padouk (10 < d ≤ 15 mm).

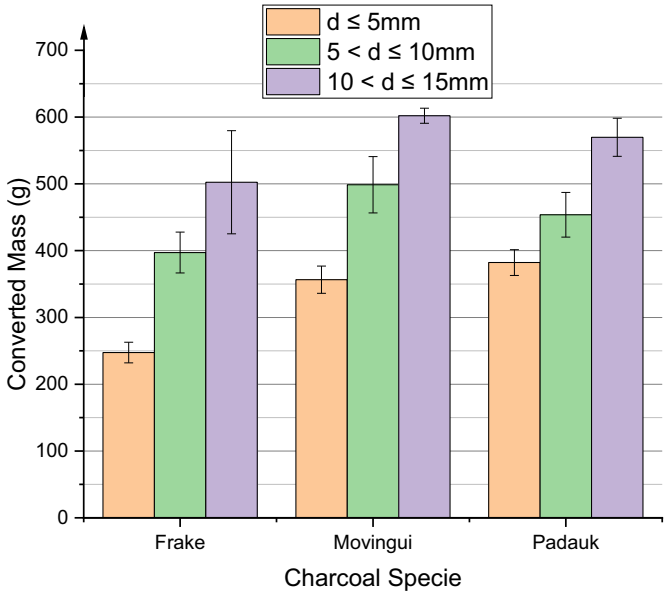

Fig. 5. Quantity of charcoal converted at the end of the gasification process.

The fixed carbon values are 71.51 % for Frake, 72.76 % for Movingui and 77.5 % for Padouk. Frake has the lowest fixed carbon while padauk has the highest, showing that the density directly affects the fixed carbon content of its charcoal. It can be seen that denser woods produce charcoal with higher fixed carbon content and vice versa. The carbon value of Movingui is in accordance with that obtained by Mfomo et al. (2020) while that for Frake obtained in this study is much higher than that found by the same authors. This difference can be attributed to the different moisture content of the biomass in the two studies.

The high heating values obtained in this study for Frake, Movingui and Padouk charcoal are 28.73 MJ/kg, 29.219 MJ/kg and 32.77 MJ/kg respectively. It can be seen that Frake charcoal which is a light wood has lowest HHV, followed by Movingui which in medium-heavy wood and finally padauk which is a heavy wood with the highest HHV. This means that physical properties such as density influence the calorific value of the biomass. The density of raw material increase with the calorific

Table 4
Estimation of gasification kinetic parameters.

Size	Biomass	Mean heating rate (°C/min)	Mass loss rate (g/min)	Converted mass fraction (%)
d ≤ 5 mm	Frake	9.54	4.12	8.25
	Movingui	15.00	5.94	11.89
	Padouk	9.67	6.37	12.74
5 < d ≤ 10 mm	Frake	18.68	6.62	13.24
	Movingui	28.76	8.31	16.62
	Padouk	15.52	7.56	15.13
10 < d ≤ 15 mm	Frake	34.79	8.37	16.75
	Movingui	36.17	10.03	20.07
	Padouk	14.45	9.50	18.99

Table 6
Mean relative error of experiments.

	Frake	Movingui	Padouk
d ≤ 5 mm	8.69 %	3.17 %	9.98 %
5 < d ≤ 10 mm	9.98 %	6.59 %	9.66 %
10 < d ≤ 15 mm	6.34 %	3.67 %	6.72 %

Table 5
Proportion of the different components of the produced syngas.

Biomass	Composition of the syngas produced					H_2/CO	LHV_{syngas} (MJ/Nm^3)	HHV_{syngas} (MJ/Nm^3)	References
	H_2 (%)	CO (%)	CO_2 (%)	CH_4 (%)	N_2 (%)				
Frake charcoal	21.88	22.32	8.93	1.56	41.61	0.98	5.72	6.23	This study
Movingui charcoal	21.47	22.79	8.57	1.51	40.68	0.94	5.71	6.22	
Padouk charcoal	20.98	23.29	7.92	1.47	41.13	0.90	5.71	6.20	
Pellets wood	21.62	27.74	9.43	2.30	38.91	0.6 to 1	6.64[a]	7.17[a]	(Aydin et al., 2019)
Pine cone	18.76	23.62	11.87	1.83	43.92	0.6 to 1.1	5.64[a]	6.1[a]	
Pine particles	23.4	32.2	15.87	19.2	–	–	13.45[a]	14.69[a]	(Niu et al., 2017)
Eucalyptus	22.3 to 22.5	22.3 to 24.3	9.8 to 10.7	1.9 to 2.1	41.5 to 42.9	–	(5.88 to 6.23)[a]	(6.41 to 6.77)[a]	(Nwokolo et al., 2020)

[a] Calculated value.

value of the charcoal produced. The results of this study are close to those of Yoon and Lee (2012) who obtained HHV of 30.31 KJ/kg, 25.28 KJ/kg, and 27.06 MJ/kg for oak charcoal, eco-coal, and bituminous coal, respectively. The HHVs obtained for this study are higher than those of bituminous coal, thus confirming from an energy point of view that the charcoal species used in this study can replace bituminous coal while reducing greenhouse gas emissions. The high HHV of the charcoal produced is crucial for a proper gasification process, as the temperature in the gasifier is maintained by the energy released from the charcoal particles in the reduction zone of the gasifier.

5.2.2. Ultimate analysis and atomic ratio

The results of the ultimate analysis and the atomic ratios (H/C and O/C) were determined and presented in Table 3. These results are compared with the literature presented by other authors.

The ultimate composition of the charcoal produced are similar for all elements studied, suggesting that it is not influenced by the characteristics of the raw wood. The carbon content is the key element in the conversion of biomass to syngas. In this study it varies from 47.3 % to 49.16 % for different species and these values are close to literature's findings (Epesse Misse et al., 2020). The hydrogen content is roughly the same for this study and the literature, with the exception of pine particles, which have higher hydrogen content. This can be attributed to their anatomical structure, which is different from the other species presented in the table. It can be seen that the proportion of oxygen is higher for raw biomass compared to charcoal. This is attributed to the carbonisation process, which causes some of the oxygen molecules in the biomass to react.

The H/C ratios considered as the index of carbonisation intensity obtained in this study vary from 1.25 to 1.28. This means that the charcoal obtained is low carbonised with minimal thermochemical alterations. This ratio is also a scale for carbonisation conditions such as charcoal stability, temperature and residence time (a low ratio indicates high temperature and long kiln residence time, which pose a risk of microbial contamination) (Meyer et al., 2017). The H/C atomic ratios obtained in this work (higher than 0.8) for the three species show sufficiently that the carbonisation process was conducted under better conditions with respect to the residence time in the kiln.

5.3. Results of gasification

5.3.1. Mass loss and temperature profile

5.3.1.1. Particles size <5 mm. The temperature variation and the mass loss profile in the gasifier during the gasification process of charcoal sizes <5 mm for each wood specie are shown in Fig. 2 below.

It can be seen that the temperature in the gasification reactor rises rapidly to >200 °C after the first 10 min for the three wood species. This corresponds to the initialisation and propagation of heat in the gasifier. The temperature behaviour is similar for the three species. It becomes almost constant after the 25th minute of gasification. The mass gradually decreases until the end of the process and differs slightly between the gasolines. The maximum temperature observed is 400 °C for Movingui, 370 °C for Frake and 340 °C for Padouk. The difference in charcoal species did not significantly influence the temperature behaviour for sizes below 5 mm, but the mass loss differs slightly between species.

5.3.1.2. Particle sizes between 5 and 10 mm. The temperature evolution and mass loss are presented in Fig. 3 below for size $5 < d \leq 10$ mm charcoal.

The temperature behaviour of the Frake and Movingui charcoals is similar. As for the smaller sizes, the temperature rises rapidly above 300 °C after 10 min of gasification. The curve becomes almost constant for the rest of the gasification time with an oscillatory tendency characterized by a rise and fall in temperature per time interval. It can be seen that the shape of the mass loss curve remains unchanged from the beginning to the end of the process for Movingui and Padouk charcoal due to the fact that the temperature remains almost constant during most of the process. The mass loss for Frake charcoal is more pronounced in places due to the temperature variations observed. The maximum temperature is 550 °C for Frake, 580 °C for Movingui, and 450 °C for Padouk. The Padouk charcoal, which has a higher density than the other two, has the lowest gasification temperature.

5.3.1.3. Particles sizes between 10 and 15 mm. Fig. 4 below shows the mass loss profile and temperature profile in the gasifier for charcoal particles between 10 and 15 mm in size.

The temperature evolves very rapidly above 400 °C after 10 min of gasification for Frake and Movingui, while a weak evolution is observed for Padouk during the first 10 min. The loss of mass is continuous during the whole process. The mass losses of Movingui and Padouk are marked by sharp drops that correspond to the intervals of high temperatures. The maximum temperatures are 730 °C for Fraké, 645 °C for Movingui and 490 °C for Padouk.

Nzali et al. (2019) carried out the gasification of *Triplochiton scleroxylon* (Ayous) sawdust in a batch reactor and obtained mass loss curves with variable rates depending on the amount of material introduced into the reactor as well as the particle size. Similarly, the mass loss curves obtained in this study differ slightly depending on the particle size and the wood species used for the charcoal. This is due to the fact that the contact surfaces of the particles in the gasifier change with the change of the charcoal particle size and also the influence of the charcoal density on the heat transfer between the charcoal particles.

The appreciation of temperature behaviour as a function of particle size for the three species demonstrate that Movingui has the highest temperature for small sizes at 400 °C and medium sizes at 580 °C followed by Frake which has 370 °C and 550 °C for small and medium sizes. But for the largest sizes, the Frake had the highest temperature at 730 °C followed by the Movingui with 645 °C. It can be seen that Padauk charcoal show the lowest temperatures for all sizes of coal particles, which are 340 °C, 450 °C, and 490 °C for small, medium and large sizes.

This behaviour can be attributed to the higher density and moisture content of the Padauk charcoal, which decreases the temperature flux in the gasification reactor. Regardless of the fuel used, the temperature in the gasifier is strongly influenced by the size of the charcoal particles. Larger particle sizes have higher gasification temperatures compared to medium and smaller particle sizes. Nzali et al. (2019) also obtained temperatures that changed with increasing particle size. This is due to the fact that increasing particle size results in a larger specific surface area and thus generates faster heating rates, leading to higher light gas production. The temperature curves show a sinusoidal pattern for the medium and large particles after 10 min of gasification. Similar temperature behaviour was observed by Aydin et al. (2019) when gasifying pine wood pellets in a fixed bed downdraft reactor with autothermal heating.

5.3.2. Mass of charcoal converted

Fig. 5 shows the average masses of converted charcoal after gasification process for each particle size.

The transformed masses for different particle sizes ($d \leq 5$ mm, $5 < d \leq 10$ mm and $10 < d \leq 15$ mm) are respectively 247.45 g, 397.15 g, 502.45 g for Frake. Movingui weighs 356.55 g, 498.65 g, and 602 g, while Padouk weighs 382.2 g, 453.75 g, and 569.8 g. From Fig. 5, it can be seen that particle size has a significant influence on the mass of charcoal converted during the gasification process. For this study, the converted masses are consistent with the temperatures in the gasification reactor for each size. The larger charcoal particle sizes reached the highest temperature, allowing for a greater mass of charcoal to be converted compared to the smaller sizes. It is concluded that as the particle sizes increase, the gasification temperatures rise to convert more biomass.

5.3.3. Kinetic analysis of gasification

Table 4 presents some parameters to characterize the syngas production process. These are: the average heating rate of the reactor, which expresses the rate of temperature increase; the mass loss rate, which estimates the average amount of biomass converted per minute; and the converted mass fraction, which expresses the percentage of feedstock converted for the same gasification time.

The gasification reactor using an autothermal heating system has average heating rates that vary significantly with particle size. The Movingui has the fastest heating rates for all particle sizes (15 °C/min, 28.76 °C/min, and 36.17 °C/min). Inter-particle heat transfer is faster for larger particles. This is due to the air flow, which is facilitated by the specific surface area, which increases with particle size and results in the fastest heating rates, as. As shown in Table 4, the mass loss rate does not vary significantly with charcoal species. It can be seen that the mass loss rate varies with particle size: it varies from 4.12 g/min to 6.37 g/min, from 6.62 g/min to 8.31 g/min, and from 8.37 g/min to 10.03 g/min for small, medium, and large particles, respectively. With an initial mass of charcoal of 3000 g in the gasifier for each experiment and an identical residence time, it can be seen that the converted mass fraction varies according to the wood species and particle size. The maximum fraction converted in 60 min for Movingui particles of size $10 \leq d \leq 15$ mm is 20.07 %. These results can be used to estimate the time required for full biomass conversion and also as a baseline for the simulation of tropical wood gasification.

5.3.4. Syngas production

In order to ensure that the gas produced is indeed hydrogen-containing syngas, it was ignited during each experiment. A continuous blue flame was observed, which confirms that the gas produced is indeed hydrogen (H_2)-containing syngas. This colour theory is confirmed by Nzali et al. (2019). The syngas produced has a low percentage of tar, indicating that it can be used in combustion engines or for power generation.

The proportions of the different gases consisting the syngas were determined empirically through equations based on elemental composition. Table 5 presents the composition of the gas produced and compares it to literature data. The heating value of the syngas is reported in the same table, assuming that the density of the syngas is close to 1 kg/m^3 as reported by Rinaldini et al. (2017).

Table 5 shows that syngas has almost the same proportions regardless all the species used in this study. The mean composition is 21.44 % of hydrogen (H_2), 22.8 % of carbon monoxide (CO), 8.47 % of carbon dioxide (CO_2), 1.51 % of methane (CH_4), and 41.14 % of nitrogen (N_2), with a H_2/CO ratio ranging from 0.90 to 0.98 with a variation rate of 1.6 %. Although the three species have different physical properties (light, medium and heavy wood), the syngas composition for these species is very close which means that the physical properties of biomass do not influence the gas yield and composition. The closeness of the gas composition for the three woods is due to the proximal composition, namely fixed carbon and volatile matter content in the charcoal. With the lower volatile matter content (20 ± 1.63 %), the padauk charcoal produced a gas with 7.92 % carbon dioxide (CO_2) content. This is a lower amount compared to the other species, with 23.29 % padauk also has the highest carbon monoxide (CO) content and this is due to its high fixed carbon content combined with the low volatile matter content. With a mean proportion of 41.14 %, nitrogen (N_2) is the major component of the gas produced, which is explained by the fact that air was used as the gasification agent in this study and that it is naturally made up mostly of nitrogen (N).

The syngas obtained for different feedstocks has calculated LHV of between 5.71 and 5.72 MJ/Nm^3. The obtained from Movingui charcoal has the best higher and lower calorific values, this is due to its high content of hydrogen and methane which are combustible gases found in synthesis gas. These results are slightly lower than the literature results in Table 5 above, but are within the range of 3.5 to 7.8 MJ/Nm^3 reported by Lui et al. (2020) to which the heating value of syngas obtained by air gasification should belong. The HHVs are between 6.20 and 6.23 MJ/Nm^3 and are in agreement with those obtained in the literature. Nevertheless, the lower and upper heating values of this study are much lower than those of Niu et al. (2017), this difference is due to the very high content of CH_4 which is a very combustible gas in the syngas obtained by this author. The above observations show that the gasification process was conducted successfully and effectively produced a syngas containing an acceptable proportion of hydrogen with respect to the gasification agent used.

5.3.5. Relative error

Table 6 presents the average relative error observed for each experiment presented above. The highest average error is less than the 10 % reference rate used by Nzali et al. (2019), demonstrating that the results of the three experiments are close enough for the experiments to be validated.

6. Conclusion

The aim of this work was to study the suitability of charcoals from three tropical wood residues for syngas production. The methodology requires first producing and characterizing charcoal, then producing syngas by air gasification, and then determining the composition and heating values of syngas. Initial chemical contents investigation shows that Movingui (*Distemonanthus benthamianus*), Padouk (*Pterocarpus soyauxii*) and Frake (*Terminalia superba*) have great characteristics for syngas production. The gas proportions of the syngas are close, with hydrogen content ranging from 20.98 % to 21.88 %, carbon monoxide (CO) content ranging from 22.2 % to 23.29 %, H_2/CO ratios ranging from 0.91 to 0.98, and syngas calorific value ranging from 4.67 to 4.96 MJ/kg.

These results showed that the density of wood residues influences the proximal properties of the charcoal produced and the particle size increases with the gasification temperature increasing the biomass

conversion. The gas produced has influenced by fixed carbon and volatile matter content of the biomass. These results also showed that the residues of the three wood species can produce syngas with low tar content and can be used in electricity generation processes or as fuel for contribute to the energetic transition.

CRediT authorship contribution statement

Benjamin Salomon Diboma: Writing – original draft, **Victor Hugo Atiotsia**, **Philipe Blaise Essomba** and **Louis Colins Ngwa**: Resources, software and experiment, **Bill Vaneck Bot**: Methodology, Writing – review & editing, Writing – original draft, **Jean Gaston Tamba**: Supervision, Project administration.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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