Evaluation of Fuel quality of Invasive Alien Plants and Tropical hardwoods as potential feedstock materials for pyro-gasification

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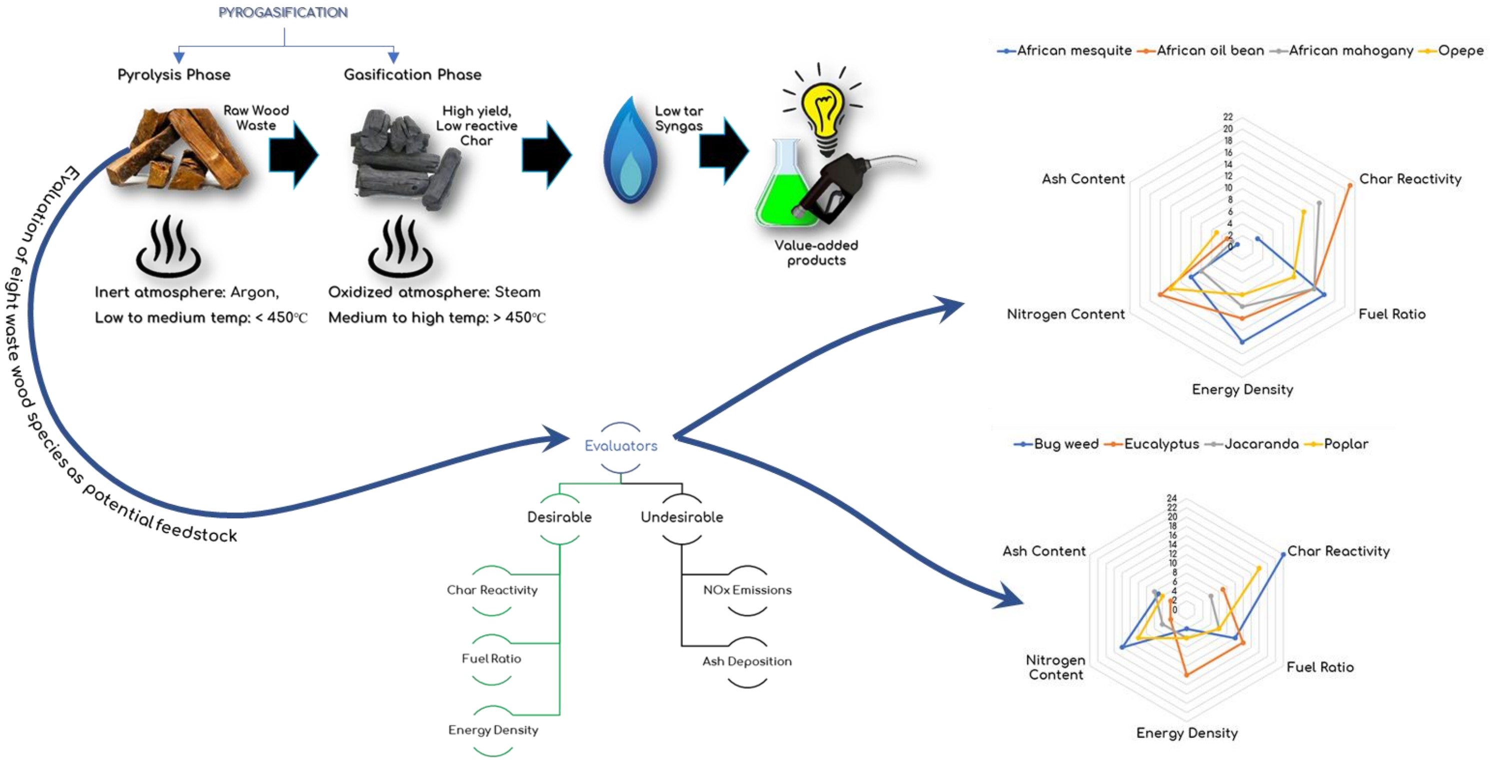
Abstract

An evaluation of the desirability of various wood feedstock derived from sawmilling wastes of eight Sub-Sahara African trees for an effective pyro-gasification conversion process was conducted. The evaluation was based solely on the characterization of the eight biomass samples. These characterizations were carried out using standard biomass feedstock characterization procedures tailored towards their use for pyro-gasification. Five fuel evaluators, including char reactivity, fuel ratio, energy density, NO_X emission, and ash deposition, of the feedstock were used as yardsticks to rank the desirability of the different biomass feedstock as fuel for an efficient pyro-gasification process. Under each evaluator, a fuel quality score between 1 – 8, with 1 being the lowest score and 8, the maximum score, was assigned to each biomass sample by considering the quality of its fuel property. This study provides relevant information to researchers to identify wood fuels prominent in Sub-Sahara Africa, which could serve as feedstock for the efficient pyro-gasification process. This study also gives an insight into the potential of using blends of biomass with distinct properties for effective co-pyrolysis and co-gasification and paves way for further research in bioenergy via thermochemical conversion of biomass.

***Keywords**: Char; Invasive Alien Plants; Pyro-gasification; Tropical hardwood; Woodfuel*

Graphical Abstract



Statement of Novelty

This study has been conducted based on original data collated from actual laboratory experiments of eight waste wood samples carried out by the authors. The evaluation of the fuel qualities of the samples as potential feedstock for pyro-gasification is the first of its kind and the methodology employed in the ranking of the samples have never been reported in literature. The following novel procedures have been carried out in this study:

1. A fuel quality evaluation of waste wood of eight invasive alien plants and tropical hardwoods in Sub-Sahara Africa based on experimental data collated from their characterization.
2. A graphical presentation of the samples based on five key fuel quality evaluators for an easy assessment of their suitability as feedstock for pyro-gasification.
3. A hierarchical ranking of the waste samples under each fuel evaluator.

1. Introduction

Biomass is any organic material derived from waste or decaying residue of plants (food crops, trees, algae) and animals [1]. It remains the only renewable resource that can be stored, and in turn, be converted to power, heat, and transport fuels. Globally, an estimated energy of 111 EJ is generated annually from the stored energy in biomass waste. This waste resource, if fully harnessed, would exceed the current global bioenergy consumption of 56.5 EJ (comprising 70% of the share of all renewable energy sources) [2, 3]. This localized and universal availability of biomass buttresses its relevance as an essential renewable energy resource. However, the efficient and sustainable utilization of waste biomass for clean energy is key to maintaining an equilibrium of the global carbon cycle and preserving the environment from degradation caused by man's incessant energy demands by exploring fossil fuels. Globally, over 800 million people are estimated to generate localized energy from agricultural biomass wastes alone [2].

Research, particularly in the beneficiation of biomass waste for energy production, has been intensified and has gained more popularity in recent years. An increased global interest inspires this research in localized and sustainable bioenergy resource supplies and improvements in efficiencies of conversion technologies. One of such conversion technologies being developed is pyro-gasification. Pyro-gasification is described as a thermochemical process enabling the independent control of the pyrolysis (drying and volatilization) and gasification stages (partial oxidation and reduction) of a conventional gasification process to eliminate the unwanted pyrolysis product (tar) before syngas production is actualized. In other words, it is a hybrid or multi-stage thermochemical process involving a combination of two independently controlled thermochemical processes (pyrolysis and gasification) running consecutively. This hybrid technology enables the formation of tar and char as intermediate products from the pyrolysis phase but restricts tar from advancing to the critical stages of syngas production (i.e. the gasification phase).

On the other hand, a carbon-rich char residue progresses as the reactant for the partial oxidation and reduction reactions of the gasification phase [4]. In the gasification phase, high char reactivity, energy density, mass, and the intermediate char's carbon-to-ash ratio are critical to an increased rate of partial oxidation and reduction reactions at lower temperatures. These char properties, in turn, contribute to the yield and fuel properties of the final syngas product.

Lignocellulosic Biomass (LCB) materials, such as waste wood, are versatile types of biomasses used as feedstocks for thermochemical and biochemical conversion processes. The efficiency of these conversion processes, to a large extent, depends on the fuel and physicochemical properties of the biomass feedstock. In pyro-gasification, to attain an optimal conversion efficiency, there is a need to utilize LCB feedstocks with the potential to form a carbon-rich and reactive char intermediate product. Asides from the effects of other factors such as gasifier type and operating conditions, the properties of the raw LCB feedstock such as the energy density, fuel ratio, higher heating value (HHV), proximate and elemental compositions (which highlight their moisture and ash content as well as its NO_X and SO_X emissions potential), serve as precursors to the properties of the char intermediate and the final syngas product [5]. The kinetics of the entire conversion process is also greatly influenced by the feedstock lignocellulosic composition [6]. This influence is particularly evident in the pyrolysis phase of a pyro-gasification process, where the thermograms of the decomposing structural components of the LCB peak at different temperatures. In this phase, the correlation between the structural composition of a biomass feedstock and the variations in the thermal decomposition patterns of its structural components is observed [6–8].

Several authors have carried out the thermochemical conversion of various biomasses and have analyzed the effect of the initial fuel properties of biomass on the final fuel properties of the char product or syngas [9–12]. In particular, Molino et al. [13] reviewed the gasification of biomass. The effect of biomass type, moisture content, and ash content was documented. Based on this review, Molino and colleagues concluded that the lignocellulosic composition of raw biomass significantly affects the syngas yield. Also, moisture content and the ash content of biomass were regarded as a negative influence on the quality of syngas produced. Chen et al. [14] reviewed the effect of improved biomass fuel properties on pyrolysis product. The torrefaction pre-treatment process was referenced as the means of upgrading biomass fuel. It was reported that properties such as Higher Heating Values, moisture content, and lignocellulosic composition, significantly affect the quality of pyrolysis product. Anukam et al. [15] studied the effect of the fuel properties of sugarcane bagasse on gasification efficiency. Torrefied and un-torrefied sugarcane bagasse, having different fuel properties, were used as feedstock for the gasification simulation. From the results obtained, Anukam and colleagues concluded that biomass/char with better initial fuel properties significantly increases the efficiency of the thermochemical conversion process. Tian et al. [16] studied the effect of biomass partial hydro-pyrolysis to produce high-quality syngas and tar. This study showed that the increase in the hydrogen content of biomass due to the partial hydro-pyrolysis process promoted the hydrogenation cracking reaction of the aromatic compounds, leading to more methane gas during the gasification process. Subsequently, the authors suggested that the alkali and alkaline earth metals significantly affect the tar oil produced during pyrolysis as it aids secondary hydrocracking. ALNouss et al. [17] carried out a study on the production of syngas using blends of various biomass. The idea of this study originated from the established knowledge that the variation of the fuel properties of different biomass feedstocks affects the quality of gas produced during the gasification process. ALNouss and colleagues suggested that the gasification of biomass blends is the way forward to utilize all kinds of biomass of different fuel qualities efficiently. Therefore, mixing biomass with low and high fuel qualities rather than regarding low-quality biomass as unusable during the thermochemical conversion process is more sustainable. Having established the significant effect of biomass types on achieving an effective pyro-gasification process, the identification and ranking of various biomass types based on their initial fuel quality are lacking in the literature.

Therefore, this study aims at the preliminary identification and ranking of some raw LCB feedstocks dominant in the Sub-Saharan African region, suitable for the formation of an ideal char intermediate in the pyrolysis phase and the subsequent efficient production of syngas in the gasification phase. The ranking technique used in this study can be applied to other types of LCBs. This study does not include the fuel analysis of the final syngas produced. However, the identification of raw LCBs with high-quality fuel properties will translate to the production of high-quality fuel syngas as established in the literature. This study would inform industry stakeholders, policymakers and researchers for future studies and commercialization of thermochemical conversion of these biomass samples and similar ones. Moreover, identifying ideal wood species would create opportunities for blending them with less suitable wood species to serve as feedstock in times of seasonal shortages in supply.

An evaluation of eight waste wood samples based on the experimental data obtained from their characterization was carried out. The waste wood samples were sourced from four Invasive Alien Plants (IAPs) mechanically controlled to curb their rapid invasion and impact on the environment in Southern Africa. They include the Jacaranda, Eucalyptus, Bugweed and Poplar. Additionally, four samples were sourced from sawmill waste of four tropical hardwoods common in Central and West Africa – African oil bean, African mesquite, African Mahogany and Opepe. Firstly, the samples were characterized for their structural composition, proximate compositions, ultimate compositions, higher heating value, bulk density, and char reactivity. Other fuel properties, such as their fuel ratios and energy densities, were derived from calculations using the experimental results. Finally, a fuel evaluation of the eight wood samples was carried out, based on the following evaluators: char reactivity, fuel ratio, energy density, nitrogen compounds emission and ash deposition.

2. Materials and methods

In preparation for the experiments, some wood lumps, due to their hardness, were first sawn into smaller blocks using a vertical band saw (Mössner Rekord SSF 520), from which sawdust produced during sawing was carefully collected in plastic sampling bags to avoid contamination. The collected sawdust was then sieved through a Sigma-Aldrich no. 40 mesh sieve with a nominal opening of 0.420 mm as used and described elsewhere [18], air-dried and stored in a desiccator to keep the samples dehydrated.

The characterization of the eight wood samples was carried out using standard procedures and equipment as listed in Table 1. To ensure the accuracy of the results, each analysis was carried out in triplicate, and average values with the standard deviations were reported.

Table 1: Characterization procedures carried out on the LCB samples

	Analysis	Equipment	Materials	Reference
1.	Structural analysis	Weighing balance (Mettler Toledo PB1502-S, USA); GESTER 250°C Lab Drying Oven GT-BM10A (China); 35L Automatic LCD Display Vertical Pressure Steam Autoclave VA-SD35 (China); FOSS XDS NIR spectrophotometer (Ireland)	Acetone, NaOH, Deionized water	[64, 135, 136]
2.	Proximate analysis	Q600 SDT thermal analyzer (TA Instruments, USA); Universal V4.5A TA Instruments Data Analysis software	Nitrogen, Oxygen	[141–143]
3.	Ultimate analysis	Flash 2000 analyzer (Thermofisher Scientific, USA)	Helium	
4.	HHV	Drycal Modular Oxygen Bomb Calorimeter	Oxygen	

5.	Bulk density	Absolute Digmatic electronic vernier calliper; Radwag PS 750.R2 weighing scale		[18, 24]
6.	Thermal reactivity (TGA)	Q600 SDT thermal analyzer (TA Instruments, USA); Universal V4.5A TA Instruments Data Analysis software	Nitrogen, Oxygen	

2.1 Structural Analysis

In determining the structural composition of the wood samples, a Soxhlet extraction was carried out on the raw sawdust of known weight, thereby leaving behind an extractives-free sample composing of hemicellulose, cellulose, and lignin. The details of the procedure adopted in this study for determining the composition of each structural component in each sample have been reported in the literature [19]. The procedure is as summarized in Figure 1.

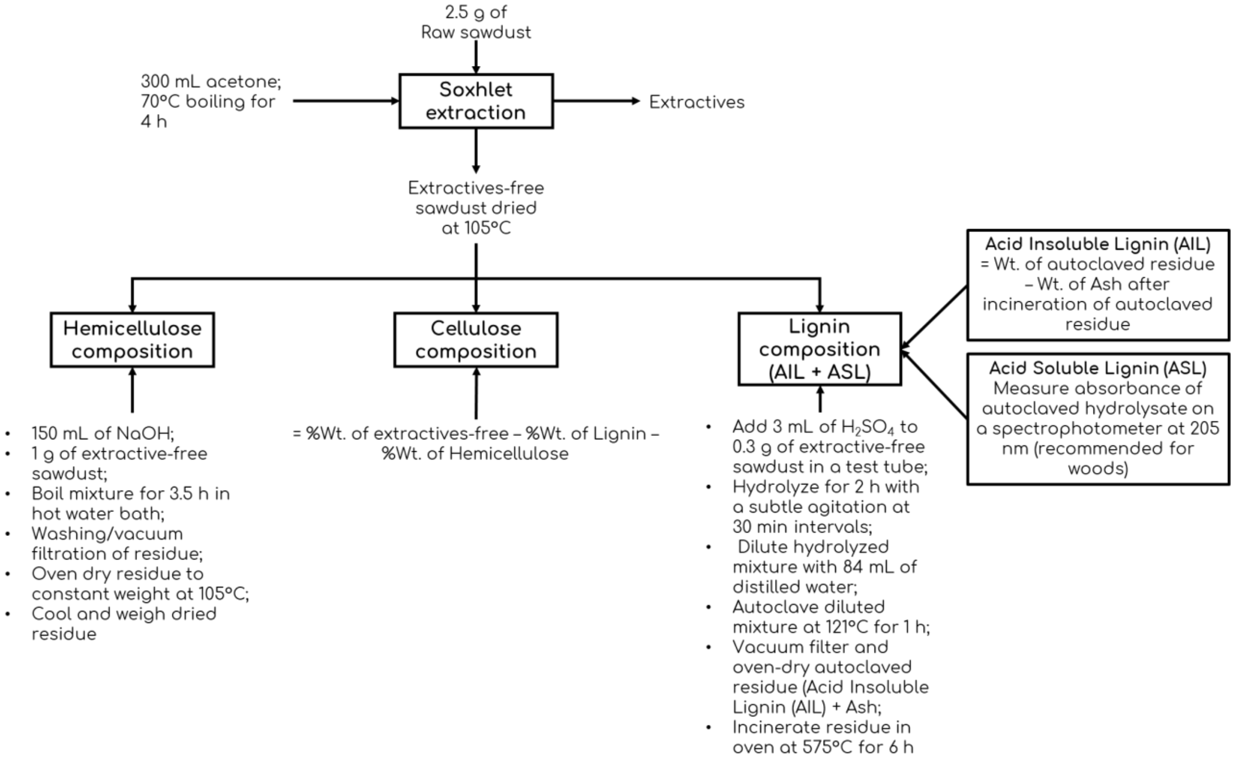


Figure 1: Structural analysis process adapted from [18]

2.2 Proximate and Ultimate Analysis

The proximate analysis was carried out on each sample by adopting standard procedures described in ASTM E1756-08, ASTM E872-82 and ASTM E1755-01 [13–15]. The fixed carbon (FC) composition was derived using Equation 1:

$$\%FC = 100 - \%(MC + VM + Ash) \tag{1}$$

Where FC = fixed carbon; MC = moisture content; and VM = volatile matter content.

The ultimate analysis was carried out on a Flash 2000 analyzer (Thermofisher Scientific, USA) connected to oxygen gas (for combustion) and helium gas (the carrier gas). This analysis was used to determine the percentage composition of C, H, N and S. The oxygen composition was derived using Equation 2:

$$\%O = 100 - \%(C + H + N + S) \tag{2}$$

C = Carbon; H = Hydrogen; N = Nitrogen; S = Sulfur; O = Oxygen

2.3 Fuel Ratio

The fuel ratio (FR) of an LCB is expressed as the ratio of its fixed carbon (FC) to its volatile matter (VM) content as obtained from its proximate analysis.

2.4 Higher Heating Value

The Higher Heating Value (HHV) of an LCB refers to the quantitative energy content of its combustible material. The HHV of the raw wood samples were determined experimentally on a Drycal Modular Oxygen Bomb Calorimeter.

2.5 Bulk and Energy Density

To determine the bulk density of the samples, lumps of the wood samples were first sawn into cubes and cuboids of known shapes. The dimensions of the woodblocks were measured using an Absolute Digmatic electronic vernier calliper to calculate their volumes. The masses of the woodblocks were determined on a Radwag PS 750.R2 weighing scale, and their bulk density was then calculated using Equation 3 [18, 24].

$$\varrho_B = \frac{Mass\ of\ wood\ block\ (g)}{Volume\ of\ wood\ block\ (cm^3)} \tag{3}$$

Where $\boldsymbol{\varrho_B}$ = Bulk density (g/cm^3).

The energy density (ED) is the energy contained in a unit volume of combustible material. This was calculated for each wood sample using Equation (4):

$$ED = \varrho_B \times HHV \tag{4}$$

Where ED = Energy density (GJ/m^3); $\boldsymbol{\varrho_B}$ = the Bulk density (g/cm^3); and HHV = Higher Heating Value (MJ/kg).

2.6 Char reactivity

By subjecting the individual wood samples to a thermal treatment, the thermogravimetric analysis (TGA) was conducted and used to obtain critical information about their thermal decomposition and the Derivative Thermogravimetry (DTG).

The procedure was carried out by loading 10 mg of each sample onto an alumina sampling cup and placed into the furnace of a Q600 SDT thermal analyzer (TA Instruments, USA). For each run, the equipment, purged with nitrogen flowing at 10 mL/min, was set at a heating rate of 10 °C/min. The process was set to run from an initial temperature of 25°C to a final temperature of 800°C and held for 30 minutes. The results obtained from the thermal analyzer were plotted and analyzed using the Universal V4.5A TA Instruments Data Analysis software.

The values of the char reactivity of the individual samples were determined with the aid of their DTG results (Table 3). The char reactivity of the samples is regarded as the peak rate of thermal decomposition of the char in the passive pyrolysis stage, as depicted in Figure 2.

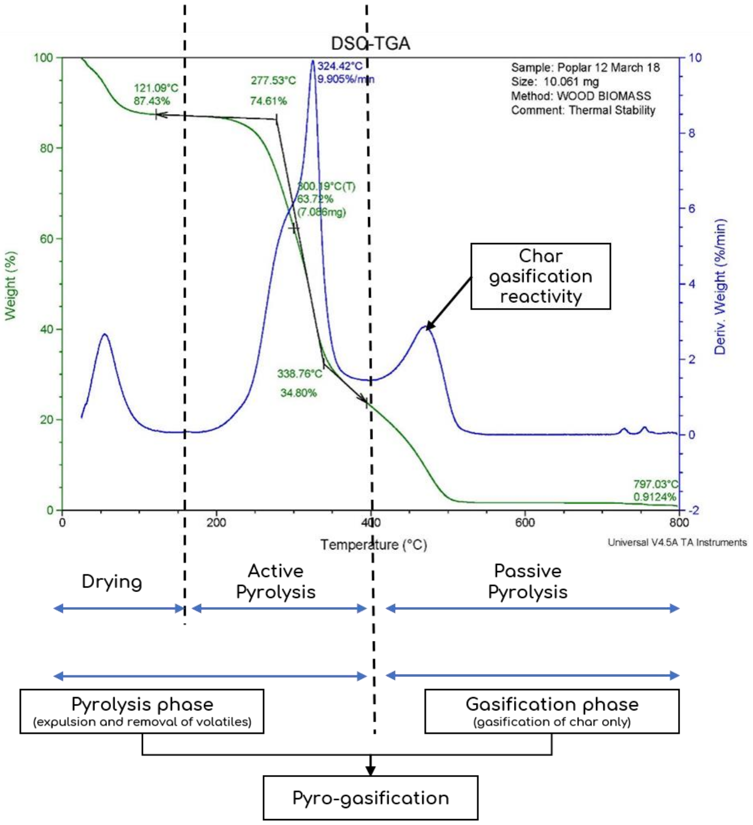


Figure 2: The thermal decomposition thermograms of Poplar its char reactivity in the passive pyrolysis stage (i.e. the char gasification phase of a pyro-gasification process)

Other thermogravimetric data, such as the initial decomposition temperature (IDT), were also derived from the wood samples' derivative thermogravimetry DTG profiles. The maximum char yield temperature and final char decomposition temperature were estimated from the weight loss profiles of the wood samples.

2.7 *Fuel evaluation exercise*

The experimental results were used in the fuel evaluation exercise to inform the five key evaluators used for this study: char reactivity, fuel ratio, energy density, Nitrogen compounds emissions, and ash deposition. These evaluators were classified as either desirable and undesirable to pyro-gasification for simplicity (see Figure 3).

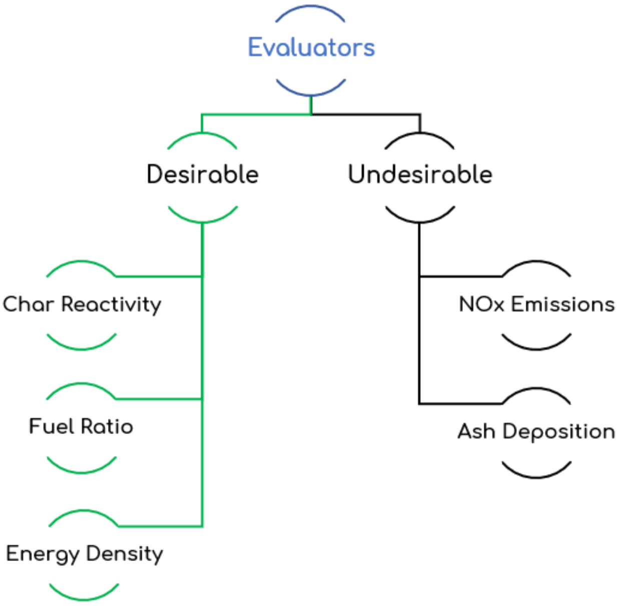


Figure 3: Classification of the evaluators

In the fuel evaluation, the following rules were employed:

a. Firstly, a *relevance factor (RF)* was assigned to each evaluator in a hierarchy of 1 to 3 based on the number of selected contributing biomass properties listed in Figure 4. For instance, the char reactivity evaluator having the highest number of contributing biomass properties was assigned an RF of 3. Meanwhile, an RF of 2 was shared by the fuel ratio, energy density and NO_x emission having an equal number of contributing biomass properties. The least RF was assigned to the ash deposition evaluator having the least number of contributing biomass properties.
b. Furthermore, a hierarchy was established among the wood samples according to the quality they exhibit under each evaluator. A *primary fuel quality rank (PFQR)* ranging from 1 (worst rank) to 8 (best rank) was assigned to each of the eight samples based on their selected biomass properties (listed in Figure 4), that contribute to an evaluator.
c. Finally, by multiplying the PFQR of a particular wood sample with the RF of an evaluator, a *secondary fuel quality score (SFQS)* was calculated for the individual samples under that evaluator (see Eq. 5).

   Wood sample A SFQS for the char reactivity evaluation:

$$\mathrm{SFQS}_{\text{sample A}} = \mathrm{PFQR}_{\text{sample A}} \times \mathrm{RF}_{\text{evaluator}} \tag{5}$$

Where *SFQS = Secondary Fuel Quality Score; PFQR = Primary Fuel Quality Rank; RF =*

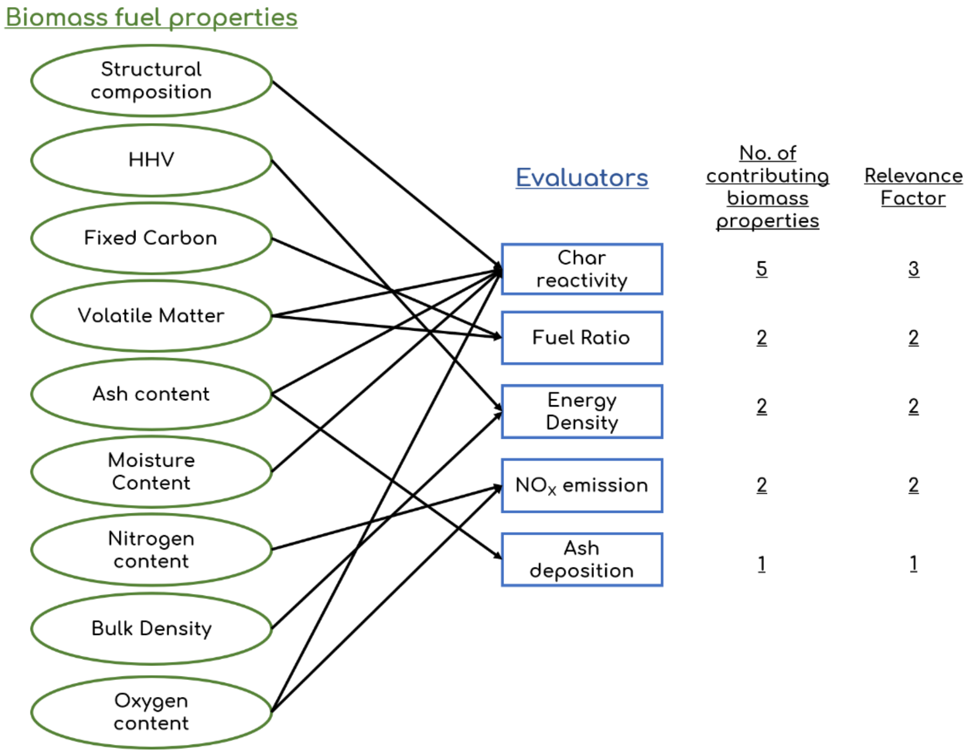


Figure 4: The five pyro-gasificaton feedstock evaluators and their respective contributing LCB fuel and physicochemical properties.

3. Results and discussion

3.1 Sample Characterization

Table 2 shows the results of the analyses carried out on the biomass samples. The average values of the analyses carried out on each sample in triplicate are reported, with the standard deviations in brackets. The standard deviation shows that the results are repeatable.

3.1.1 Structural analysis

The lignocellulosic composition of an LCB and its secondary cell wall structure is one of the primary contributors to its physical and chemical characteristics, distinguishing it as an ideal feedstock for conversion to specific biofuels either by biochemical or thermochemical conversion process [25].

Figure 5 compares the lignocellulosic compositions of the biomass species investigated in this study. The Bug weed biomass exhibit the highest cellulose composition of 31.31 wt. % and a total holocellulose (cellulose and hemicellulose) composition of 67.31 wt. %. This is closely followed by the Jacaranda (65.21 wt. % holocellulose). The lignin composition of the samples ranges from 26.67 wt. % to 43.33 wt. %. Considering its higher holocellulose and lower lignin composition, the Bug weed exhibits high char reactivity. This observation is due to the high rates of thermal decomposition typically exhibited by holocellulose. However, the Bug weed's high holocellulose and low lignin composition may also classify it as an ideal feedstock for biochemical conversion processes.

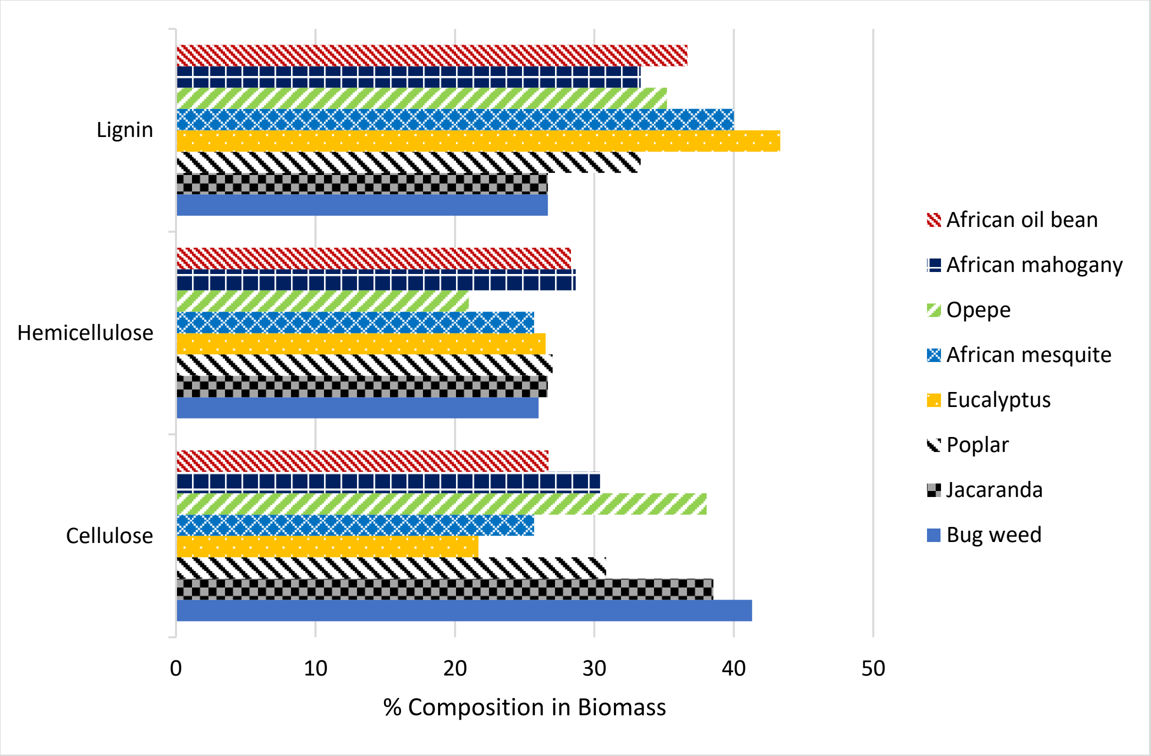


Figure 5: A comparison of the structural compositions of the eight wood samples

Conversely, the lignin composition is generally higher in the hardwoods – Eucalyptus and Poplar. The contribution of lignin to wood, such as mechanical strength, hydrophobicity and resistance to pest and microbial attack, further underlines its importance [19, 20]. In some instances, high lignin composition can be found in softwoods, particularly those with thicker barks due to the high amounts of lignin contained in barks of trees. In this study, however, the sawdust samples were sourced from the sapwood and heartwood of the tree trunk.

As reported, lignin exhibits higher heating values than holocellulose due to its lower rate of oxidation or decomposition [20, 21]. In most cases, the average difference between the HHV of hardwoods and softwoods is basically due to the difference in their lignin composition. This observation corroborates with the results of the samples investigated in this study, as seen in Table 2.

Table 2: Experimental analysis of the eight wood samples

Analysis		**BIOMASS**								**Recommendations for wood fuels**	
		Eucalyptus	**Bugweed**	**Poplar**	**Jacaranda**	**African mesquite**	**Opepe**	**African mahogany**	**African oil bean**	**Austria ONORM M7135**	**German DIN51731 /DINplus**
Lignocellulosic analysis %	**Cellulose**	21.68 (±0.27)	41.31 (±0.28)	30.84 (±0.61)	38.54 (±0.54)	25.69 (±0.40)	38.05 (±0.25)	30.40 (±0.45)	26.71 (±0.31)		
	Hemicellulose	26.51 (±0.49)	26.00 (±0.29)	27.01 (±0.62)	26.67 (±0.21)	25.67 (±0.56)	21.00 (±0.56)	28.67 (±0.69)	28.33 (±0.21)		
	Lignin	43.33 (±0.57)	26.67 (±0.66)	33.33 (±0.96)	26.67 (±0.91)	40.00 (±0.94)	35.20 (±0.21)	33.33 (±0.28)	36.67 (±0.16)		
	Extractives	8.48 (±0.93)	6.02 (±0.47)	8.82 (±0.29)	8.12 (±0.42)	8.64 (±0.23)	5.75 (±0.49)	7.60 (±0.49)	8.29 (±0.36)		
Proximate analysis %	**MC**	9.13 (±0.52)	8.93 (±0.30)	12.21 (±0.36)	9.12 (±0.10)	9.61 (±0.73)	7.16 (±0.74)	7.21 (±0.40)	8.56 (±0.15)		
	VM	49.88 (±0.80)	54.92 (±0.33)	56.56 (±0.52)	57.91 (±0.45)	43.29 (±0.38)	58.65 (±0.41)	52.12 (±0.57)	51.01 (±0.33)		
	FC*	39.98	34.44	30.20	30.76	47.11	33.17	40.36	39.86		
	Ash	1.01 (±0.36)	1.74 (±0.12)	1.04 (±0.18)	2.21 (±0.29)	0.10 (±0.05)	1.02 (±0.08)	0.40 (±0.31)	0.58 (±0.09)	≤0.5	<1.5/<0.5
Ultimate analysis %	**C**	47.82 (±0.94)	43.33 (±0.91)	42.34 (±0.14)	44.23 (±0.70)	50.49 (±0.45)	48.62 (±0.22)	48.42 (±0.18)	45.64 (±1.02)		
	H	5.37 (±0.07)	5.66 (±0.81)	5.82 (±0.18)	5.73 (±0.31)	5.63 (±0.22)	6.02 (±0.40)	5.81 (±0.22)	5.81 (±0.27)		

	N	0.08 (±0.02)	0.40 (±0.09)	0.27 (±0.02)	0.18 (±0.04)	0.26 (±1.16)	0.37 (±0.06)	0.19 (±0.04)	0.40 (±0.05)	<0.3	<0.3
	S	0	0	0	0	0.01	0	0	0	<0.04	<0.08/0.04
	O*	46.73	50.75	51.58	49.87	43.61	44.99	45.59	48.16		
HHV (MJ/kg)		18.84 (±0.38)	17.58 (±0.29)	18.80 (±0.31)	18.43 (±0.21)	20.72 (±0.33)	18.90 (±0.25)	19.34 (±0.29)	19.15 (±0.25)	>18.0	17.5 - 19.5/ >18
Bulk density (g/cm^3)	**ϱB**	1.01 (±0.12)	0.40 (±0.04)	0.50 (±0.01)	0.51 (±0.02)	1.05 (±0.03)	0.67 (±0.02)	0.66 (±0.04)	0.95 (±0.02)		
Energy density (GJ/m^3)	**ED**	19.03	7.03	9.40	9.40	21.76	12.66	12.76	18.19		
Fuel Ratio FC/VM	**FR**	0.80	0.63	0.53	0.53	1.08	0.60	0.80	0.80		

***** by difference. Standard deviation in bracket. MC=moisture content; VM= Volatile Matter, FC= Fixed Carbon; C= Carbon; H = Hydrogen;

N = Nitrogen; S = Sulfur; O = Oxygen.

The structural components also contribute primarily to the mass of the char intermediate formed in the pyrolysis phase. A greater char mass may be expected from tree species such as the Eucalyptus and the African mesquite, exhibiting relatively higher amounts of lignin – 43.33 wt. % and 40 wt. % respectively. Conversely, low char mass may be expected from species such as the Bug weed and Jacaranda due to their very low lignin compositions of 26.67 wt. %. However, this may not necessarily be the case. Yu *et al*. [29] reported on the complexity of the biomass pyrolysis process, whereby the three components (cellulose, xylan (hemicellulose), and lignin) show overlapping decomposition thermograms. Despite the lignin decomposition contributing primarily to char formation, hemicellulose also acted as a secondary contributor to char formation. This is so because while hemicellulose attains its peak rate of decomposition at a much lower temperature than the other components, it is observed to achieve thermal stability around 400°C. Hemicellulose decomposition is therefore extended beyond the active pyrolysis zone and into the passive pyrolysis zone, following a decomposition trend like that of lignin. In this passive zone, only the char intermediate is left to decompose. This passive pyrolysis zone also represents the gasification phase of a pyro-gasification process (see Figure 2).

Table 3 shows the thermal properties of the biomass samples as analysed using a Thermogravimetric Analyzer. As seen in Tables 2 and 3, it may be concluded that the high char reactivity of the Bug weed is attributed to the high hemicellulose fraction in its intermediate char product. This implies that larger composition of hemicellulose favours a high gasification conversion rate of the intermediate char product. However, high amounts of hemicellulose in the Bug weed, Poplar, and Jacaranda also indicate their potential to produce high quantities of tar-forming volatiles during pyro-gasification. Furthermore, biomass species such as African Mesquite and Eucalyptus exhibit low biomass reactivity of 0.87 and 1.19 %/min, respectively. These observations can be attributed to the fact that the hemicellulose to lignin ratio in their intermediate char product may be lower. However, Jacaranda biomass has low lignin fractional composition and low reactivity.

Table 3: Thermal properties of wood samples

Biomass	**Initial decomposition temp.**	**Char reactivity**	**Burnout temp.**
	°C	**%/min**	**°C**
Bug weed	179	3.13	475
Jacaranda	170	0.95	785
Poplar	185	2.87	510
Eucalyptus	171	1.19	795
Opepe	180	1.37	660
African oil bean	198	3.07	515
African mahogany	202	1.70	640
African mesquite	183	0.87	>800

Furthermore, as shown in Tables 2 and 3, it can be observed that the wood samples with high lignin content have very high burnout temperatures. This observation implies that higher energy input is required to gasify an LCB with high lignin composition. However, this does not render biomass with high lignin content inefficient for the thermochemical conversion process as lignin also contributes to the energy density of biomass. Therefore, from these observations, a clear conclusion on which biomass species is most favourable for pyro-gasification cannot be made. However, a combination of other fuel properties can provide a scientific conclusion.

3.1.2 Proximate analysis

The proximate analysis of eight biomass species is reported in Table 2. One of the limitations of biomass for effective thermochemical conversion is its moisture content [30]. This is observed to be high in Poplar (12.21 wt. %). The presence of high moisture content in biomass would reduce the efficiency of a pyro-gasification process. This is because some of the heat supplied in the gasification phase eliminates the water content in biomass rather than produce syngas. Also, high moisture in biomass contaminates the tar oil produced in the pyrolysis phase, thereby requiring further refining. However, pre-treatment processes such as torrefaction and solvolysis methods have proved to address these drawbacks. Another negative impact of high moisture content in biomass is the cost of transportation of biomass. When biomass with high moisture content is transported, a fraction of the transport fuel is used to transport water, thereby adding to transportation costs.

Al-Zareer et al. [31] studied the effect of some gasification parameters and biomass type on the syngas composition. With the aid of a gasification simulation process, volatile matter of biomass was observed to favour the production of hydrogen-rich syngas. Based on this observation, biomass species such as Opepe with a relatively high volatile matter may favor the production of hydrogen-rich syngas. However, rather than considering volatile matter alone, the fuel ratio (fixed carbon/volatile matter) is used to determine the desirability of wood fuel for an effective pyro-gasification. Good wood fuel is considered as one with a high fuel ratio [32]. Hence, it is required that a good fuel possess a volatile matter content that is significantly less than the fixed carbon. As seen from Table 1, only the African mesquite has its fixed carbon higher than its volatile matter. This suggests that raw African mesquite can serve as a suitable feedstock for an effective pyro-gasification process. However, the fuel ratio of the biomass species studied can be improved using pre-treatment processes such as torrefaction and solvolysis [32, 33].

Hernández et al. [34] carried out the techno-economic analysis of using biomass in power plants. The result shows that biomass ash content significantly reduces the heating value of the fuel. As seen from Table 2, according to the Austria ONORM M7135 and German DIN51731/DINplus, a recommended wood fuel for the thermochemical conversion process should have an ash content of less than 0.5 wt. %. Only African mesquite and African mahogany satisfy this requirement. In this study, the effect of high ash content is also observed with the Jacaranda. The Jacaranda, with the highest ash content (2.21%), is observed to exhibit a very low char reactivity of 0.95 %/min (see Table 3), despite its high holocelluse composition. A common occurrence in the gasification of biomass which is also expected in pyro-gasification is the deposition of layers of ash residues containing reaction-inhibiting silicone particles on the char surface. These ash layers block char pores and inhibit the free transfer of hot oxidizing gases into their inner carbon particles. This thereby minimizes the rate of char partial oxidation and conversion of the inner carbon particles [35–37]. Therefore, despite exhibiting fuel properties favourable for pyro-gasification, an LCB with a high ash content could exhibit low char conversion in the gasification phase. Table 4 compares the fuel ratios derived from the volatile matter and fixed carbon values of the samples in this study with other LCB materials reported in the literature. The ash content of other LCBs reported in the literature is also listed in Table 5.

Table 4: A comparison of the fuel ratio of samples in this study with those derived from literature.

WOOD AND WOODY BIOMASS	VM %	FC %	FUEL RATIO	REFERENCE
Eucalyptus	48.88	39.98	0.8	This study
Bugweed	54.92	34.44	0.63	This study
Poplar	56.56	30.2	0.53	This study
Jacaranda	57.91	30.76	0.53	This study
African mesquite	43.29	47.11	1.08	This study
Opepe	58.65	33.17	0.60	This study
African mahogany	52.12	40.36	0.80	This study
African oilbean	51.01	39.86	0.80	This study
Poplar bark	73.6	16	0.22	[49, 156]
Tamarack bark	63.7	24.1	0.38	[49, 156]
Spruce bark	67.3	21.4	0.32	[49, 156]
Pine bark	70.2	23.3	0.33	[49, 156]
Elm bark	67	17.2	0.26	[49, 156]
Maple bark	70.1	17.8	0.25	[49, 156]
Balsam bark	70.9	18.3	0.26	[49, 156]
Beech bark	65	23.9	0.25	[49, 156]
Birch bark	71.7	17.8	0.25	[49, 156]
Eucalyptus bark	68.7	15.1	0.22	[40]
Hemlock bark	65.9	23.4	0.36	[49, 156]
Oak wood	77.6	21.9	0.28	[49, 158]
Olive wood	74.3	16.1	0.22	[49, 159]
Pine wood	76.50	14.45	0.19	[43]
Spruce wood	71.0	14.4	0.20	[43]
Willow wood	74.2	14.3	0.19	[49, 161]
Alder-fir wood	36.3	9.1	0.25	[49, 162]
Poplar wood	79.7	11.5	0.14	[49, 162]
Hybrid Poplar wood	78.97	11.63	0.15	[45]
Christmas tree wood	46.02	12.93	0.28	[49, 162]
Red oak wood	76.35	11.92	0.16	[45]
Beech wood	82.5	17.0	0.21	[41]

Despite the samples in this study exhibiting high volatile matter contents comparable to those of other woody biomass samples reported in the literature, their fixed carbon contents were, however, observed to be higher than those of most other biomass. This disparity may be attributed to variations in moisture contents and ash contents common with biomass due to growth conditions, storage, and handling. Moreover, as previously mentioned, moisture and ash content may vary between wood samples of the same species. This is possible if both samples were harvested in different geographical and climatic locations or harvested from different parts of the same tree. The wood samples evaluated in this study were harvested from the trunks of trees and stem in the case of the Bug weed. As reported in a study by Duruaku et al. [18], comparing the fuel properties of the main branches and trunks of 11 tropical trees, wood samples harvested from the trunks exhibited better fuel properties than their counterparts sourced from the main branches of the same tree.

Table 5: A comparison of the ash content of the samples in this study with those reported in the literature.

WOOD AND WOODY BIOMASS	ASH CONTENT	REFERENCE
	wt%	
Bugweed	1.74	This study
Eucalyptus	1.01	This study
Poplar	1.04	This study
Jacaranda	2.21	This study
African mesquite	0.01	This study
Opepe	1.02	This study
African mahogany	0.08	This study
African oil bean	0.58	This study
Poplar bark	2.0	[38, 39]
Tamarack bark	3.8	[38, 39]
Spruce bark	2.9	[38, 39]
Pine bark	1.8	[49, 156]
Elm bark	7.4	[49, 156]
Maple bark	3.7	[49, 156]
Balsam bark	2.4	[49, 156]
Beech bark	7.1	[49, 156]
Birch bark	1.9	[49, 156]
Eucalyptus bark	4.2	[40]
Hemlock bark	2.3	[49, 156]

Oakwood	0.5	[49, 158]
Olive wood	3.0	[49, 159]
Pinewood	5.5	[49, 160]
Spruce wood	0.5	[49, 160]
Willow wood	1.4	[49, 160]
Alder-fir wood	2.0	[49, 159]
Poplar wood	2.0	[49, 161]
Hybrid Poplar wood	0.04	[45]
Christmas tree wood	0.3	[49, 161]
Red oak wood	0.3	[45]
Beech wood	0.5	[41]

3.1.3 Ultimate analysis

The ultimate analysis, also known as the elemental biomass composition, greatly determines its suitability as a raw material for syngas production. Biomass species with a low hydrogen-to-carbon ratio and low oxygen-to-carbon ratio could be considered efficient as feedstock for thermochemical conversion processes [47]. Research efforts made by Nhuchhen and Afzal [48] on predicting the heating value of biomass via its ultimate analysis suggested that the carbon content of biomass positively affects the heating value while oxygen negatively affects the heating value of biomass. Hence, scientifically, good wood fuel is considered as one which has a low oxygen-to-carbon ratio. As seen in Table 2, Bug weed, Poplar, Jacaranda, and African oil bean biomass species have oxygen-to-carbon ratios greater than 1. This implies that these biomass species lack the attribute of a good fuel in terms of its ultimate analysis. However, these fuel properties can be improved through pre-treatment processes.

Table 6 shows similarities in the nitrogen contents of the samples in this study with those reported in the literature. Likewise, other biomass properties, the nitrogen content of a particular plant or variety of plants may vary depending on factors such as the type of soil, the climatic conditions and the proximity of a nitrogen compounds emitting factory to the location where the biomass is grown.

Table 6: A comparison of the nitrogen content of the samples in this study with those of other LCBs reported in the literature

WOOD AND WOODY BIOMASS	NITROGEN CONTENT	LITERATURE
Bugweed	0.4	This study
Eucalyptus	0.08	This study
Poplar	0.27	This study
Jacaranda	0.18	This study
African mesquite	0.26	This study
Opepe	0.37	This study
African mahogany	0.19	This study
African oil bean	0.40	This study
Poplar bark	0.6	[49, 156]
Tamarack bark	0.7	[49, 156]
Spruce bark	0.1	[49, 156]
Pine bark	0.3	[49, 156]
Elm bark	0.7	[49, 156]
Maple bark	0.4	[49, 156]
Balsam bark	0.2	[49, 156]
Beech bark	0.7	[49, 156]
Birchbark	0.5	[49, 156]
Eucalyptus bark	0.3	[40]
Hemlock bark	0.2	[49, 156]
Oakwood	0.3	[49, 158]
Olive wood	0.7	[49, 159]
Pinewood	0.5	[49, 159]
Spruce wood	0.3	[49, 159]
Willow wood	0.6	[49, 161]
Alder-fir wood	0.5	[49, 162]
Poplar wood	0.6	[49, 162]
Hybrid Poplar wood	0.04	[45]
Christmas tree wood	0.3	[49, 162]
Red oak wood	0.03	[45]
Beech wood	0.4	[41]

3.1.4 Energy content

The higher heating value (HHV) of any wood fuel is a critical fuel property that determines its suitability for an effective thermochemical conversion process. Although other operating conditions affect the energy content of the final syngas, the initial energy content of the wood fuel significantly affects the final higher heating value of the syngas. According to the German DIN51731, a good fuel is considered as one whose HHV is greater than 17.5 MJ/kg (see Table 2). All the biomass HHVs exceed this value and are close to the recommended values by the Austria ONORM M7135 and the German DINplus. Therefore, these samples may be considered suitable for their high energy content. The energy density captures the energy content present in one cubic meter of wood. This parameter is usually critical when considering the palletization of biomass for cooking or heating homes. Unlike other physicochemical properties of biomass, the higher heating values of the wood samples used for this study are more predictable and consistent with those reported in the literature (see Table 7).

Table 7: A comparison of the Higher Heating Values of wood samples in this study and other studies.

BIOMASS	**HHV** **(MJ/kg)**	**REFERENCE**
Bug weed	**17.58**	This study
	16.9	[46]
Jacaranda	**18.43**	This study
	-	
Poplar	**18.80**	This study
	19.38	[27]
	18.57	[43]
Eucalyptus	**18.84**	This study
	18.64	[49]
Opepe	**18.90**	This study
	21.44	[18]
African oil bean	**19.15**	This study
	20.06	[18]
African mahogany	**19.34**	This study
	20.79	[18]
African mesquite	**20.72**	This study
	22.41	[18]
Hog wood	*20.95*	[45]
Hybrid Poplar	*18.95*	[45]
Willow tree	*18.79*	[43]
Pine tree	*19.38*	[43]
Birch tree	*19.34*	[43]

3.2 Uncertainty analysis

3.2.1 Absolute uncertainty

The absolute uncertainty (standard deviation) of each experimental measurement was calculated using the three values obtained when each experiment was carried out in triplicate, as reported in Table 2. These values are presented in brackets and assigned the "±" sign. The reported standard deviations were low, indicating minimal and acceptable errors. However, a relative uncertainty analysis is required to compare the magnitude of the standard deviations with its measured values to ensure the accuracy of the experiments. As shown in Table 2, some fuel properties were calculated using some measured values. To carry out the relative uncertainty analysis (Eq. 8) of the measured and calculated fuel properties, their corresponding absolute errors were calculated. The absolute error values for the calculated fuel properties were derived using the propagation of error analysis as described below. Whereas, the absolute errors for the measured fuel properties are represented by their standard deviation presented in Table 2.

3.2.2 Propagation of error analysis

Propagation of error analysis helps to check the effect of the variables' uncertainties on the uncertainty of a calculated figure or function based on those variables. For each function type, there are different ways of carrying out this analysis. For example, this analysis provides the absolute errors of the calculated fuel properties: % Oxygen content, energy density, fixed carbon content, and the fuel ratio.

For calculated fuel properties involving additions and subtractions, Equation 6 is used to calculate their absolute errors. Whereas, Equation 7 was used for the functions involving multiplications and divisions.

$$\Delta Y = \Delta X_1 + \Delta X_2 + \Delta X_3 + \ldots + \Delta X_n \tag{6}$$

$$\frac{\Delta Y}{Y} = \frac{\Delta X_1}{X_1} + \frac{\Delta X_2}{X_2} + \frac{\Delta X_3}{X_3} + \ldots + \frac{\Delta X_n}{X_n} \tag{7}$$

3.2.3 Relative uncertainty analysis

Since some experimental runs were done to arrive at the ranking decisions, it is paramount to see the uncertainty in the experimental measurement compared to the actual measured values [50, 51]. Therefore, this analysis provides a basis to show the reliability of the measured values and subsequently the ranking of the different biomass which is based on their fuel properties. Equation 8 was used to carry out this analysis. The relative uncertainties are reported in Table 8.

$$Relative\ Uncertainty = {}^{absolute\ error}\!/_{measured\ value} \tag{8}$$

As seen in Table 8, the measured fuel properties of the biomass samples obtained during the experiments exhibited relatively low relative uncertainty of less than 20% except for ash having a relative uncertainty of 40%, 50%, and 80% for Eucalyptus, African mesquite, and African mahogany.

This shows the difficulty in quantifying the actual ash content in biomass. However, the average of the three values for each biomass was used for further analysis to reduce the uncertainty influence on the ranking. Furthermore, the uncertainty in the calculated values derived by propagating the variables' uncertainties was relatively low, with a maximum of 14% for the energy density of the Eucalyptus biomass.

Having carried out the uncertainty analysis of these experimental measurements, it can be concluded that these results are dependable. Hence, validating the biomass ranking.

Table 8: The relative uncertainty of the measured and calculated fuel properties of the eight biomass samples.

Analysis		Eucalyptus	Bugweed	Poplar	Jacaranda	African mesquite	Opepe	African mahogany	African oil bean
Lignocellulosic analysis %	Cellulose	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.01
	Hemicellulose	0.01	0.01	0.02	0.01	0.02	0.03	0.02	0.01
	Lignin	0.01	0.02	0.03	0.03	0.02	0.01	0.01	0.01
	Extractives	0.11	0.08	0.03	0.05	0.03	0.09	0.06	0.04
Proximate analysis %	MC	0.06	0.03	0.03	0.01	0.08	0.10	0.06	0.02
	VM	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	FC	0.04	0.02	0.04	0.03	0.02	0.04	0.03	0.01
	Ash	0.40	0.07	0.17	0.13	0.50	0.08	0.80	0.16
Ultimate analysis %	C	0.02	0.02	0.01	0.02	0.01	0.01	0.01	0.02
	H	0.01	0.14	0.03	0.05	0.04	0.07	0.04	0.05
	N	0.20	0.20	0.06	0.20	0.12	0.15	0.20	0.12
	S	-	-	-	-	-	-	-	-
	O	0.02	0.04	0.01	0.02	0.04	0.02	0.01	0.03
HHV (MJ/kg)		0.02	0.02	0.02	0.01	0.02	0.01	0.02	0.01
Bulk density (g/cm^3)	ϱB	0.12	0.10	0.02	0.04	0.03	0.03	0.06	0.02
Energy density (GJ/m^3)	ED	0.14	0.12	0.04	0.05	0.04	0.04	0.08	0.03
Fuel ratio (-)	FR	0.06	0.03	0.04	0.04	0.04	0.05	0.04	0.03

3.3 Fuel Quality Evaluation

Figures 6 a and b are graphical summaries of the SFQS of the eight waste wood samples under each feedstock evaluator. These charts are clear and concise representations of the scale at which the fuel properties of the different wood species are suitable for pyro-gasification. A hierarchy of the wood samples under each evaluator is also represented in Fig. 7. These would aid stakeholders and policymakers engage in quick and informed decisions to select suitable feedstock for pyro-gasification. A wood species could be selected to be pyro-gasified individually or as a blend of two or more species exhibiting contrasting properties in suitable mix ratios. By so doing, the effect of seasonal shortages in the supply of a particular feedstock could be minimized.

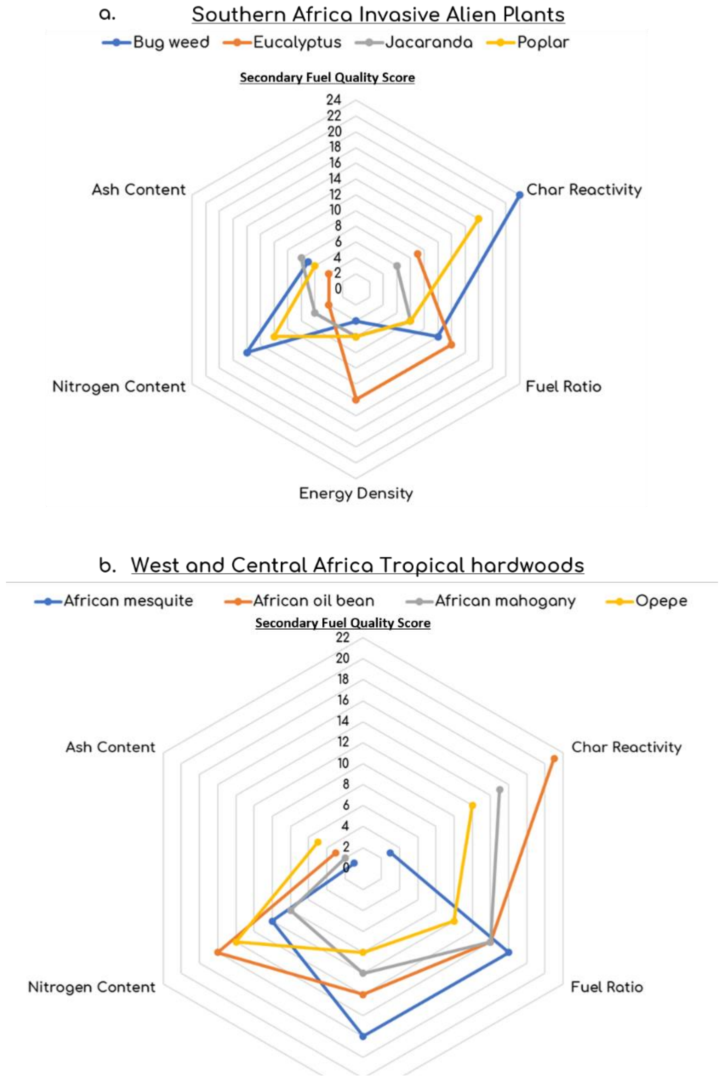


Figure 6: A graphical representation of the (a.) Southern Africa invasive alien wood samples, and (b.) West and Central Africa Tropical hardwoods, based on their Secondary Fuel Quality Score under each evaluator

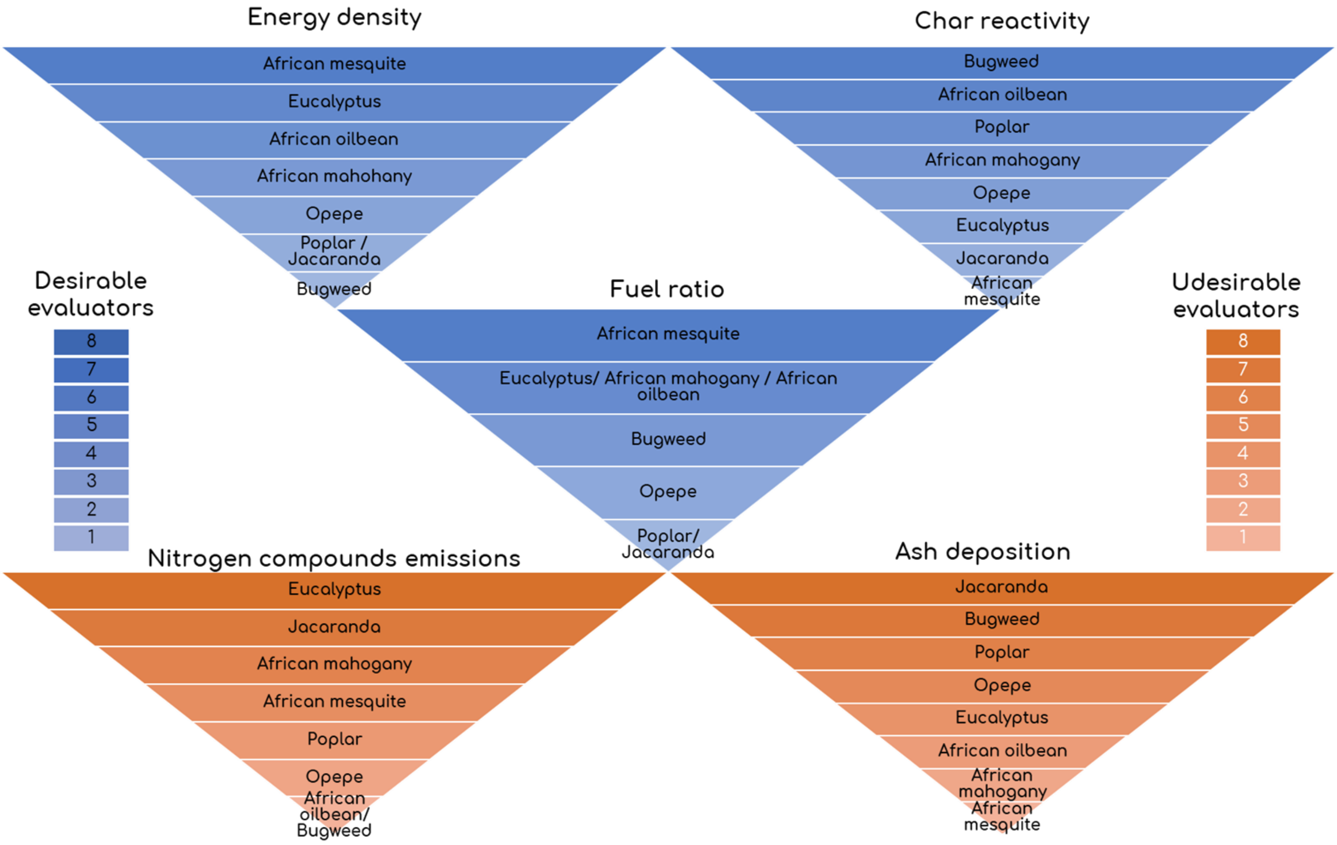


Figure 7: A hierarchy of the wood samples under each evaluator

The char reactivity of the wood samples is an important yardstick for the feedstock evaluation of the wood samples for pyro-gasification due to its direct influence on the gasification phase reactions, as earlier discussed. High biomass reactivity permits early syngas production by aiding the activation of the gasification reactions at lower gasification temperatures, thereby requiring less energy input. A low biomass char reactivity as observed with the African mesquite could lead to poor, inadequate or incomplete conversion of the char intermediate's carbon component, particularly at low temperatures in the gasification phase of a pyro-gasification process. Therefore, a higher activation energy and energy input would be required to trigger a complete conversion of the char to syngas. This could also influence the syngas composition and yield.

Biomass fuel ratio affects the properties of the pyrolysis phase products, which in turn affect the quality, composition and yield of the final syngas produced [27, 28]. The high amounts of VM and relatively low FC of solid biomass fuels makes them more reactive and less energy-dense than coal [54]. Since high volatile matter content in biomass is a desirable property for a quick ignition when blended with coal for combustion, higher amounts of fixed carbon are most desired to promote syngas yield in the gasification phase. In this phase, triggering a quick ignition would lead to absolute combustion of the char in the presence of the oxidizer. Moreover, as previously mentioned, the presence of tar-forming volatiles generated by biomass affect syngas quality and limit its end use for downstream applications [55]. Therefore, samples with higher fuel ratios (*i.e.* Higher FC and lower VM) are considered most desirable for pyro-gasification.

Table 9: Fuel evaluation scores of wood samples

		BIOMASS															
PARAMETER	**RF**	**Bug weed**		**Eucalyptus**		**Jacaranda**		**Poplar**		**African mesquite**		**African oil bean**		**African mahogany**		**Opepe**	
		PFQR	***SFQS***	*PFQR*	***SFQS***	*PFQR*	***SFQS***	*PFQR*	***SFQS***	*PFQR*	***SFQS***	*PFQR*	***SFQS***	*PFQR*	***SFQS***	*PFQR*	***SFQS***
Char Reactivity	3	8	**24**	3	**9**	2	**6**	6	**18**	1	**3**	7	**21**	5	**15**	4	**12**
Fuel Ratio	2	6	**12**	7	**14**	4	**8**	4	**8**	8	**16**	7	**14**	7	**14**	5	**10**
Energy Density	2	2	**4**	7	**14**	3	**6**	3	**6**	8	**16**	6	**12**	5	**10**	4	**8**
Nitrogen compds	2	8	**16**	2	**4**	3	**6**	6	**12**	5	**10**	8	**16**	4	**8**	7	**14**
Ash content	1	7	**7**	4	**4**	8	**8**	6	**6**	1	**1**	3	**3**	2	**2**	5	**5**

RF (Relevance Factor of evaluator); PFQR (Primary Fuel Quality Rank); SFQS (Secondary Fuel Quality Score).

Biomass containing low values of elemental nitrogen and sulfur contents are desirable for pyro-gasification and other thermochemical conversion processes [56]. Incombustible nitrogen compounds – N_2, NO_X (NO, NO_2), N_2O are formed during thermochemical processes and are emitted into the atmosphere, while NH_3 and HCN are undesirable for syngas downstream applications. However, due to the small quantity of sawdust tested, the effects of the nitrogen composition of the samples was not significant. Within the scope of this study, any gaseous nitrogen compounds present in the syngas was not detected. Meanwhile, as earlier observed, the sulfur content of the samples evaluated was negligible, and therefore sulfur composition was not considered as part of the evaluation. Asides from the negative impacts caused by emitting nitrogen compounds, wood nitrogen content were more important in this study as plant biomass is often known to contain significant amounts of nitrogen, particularly when grown on agricultural-active soils. Naturally, soils contain an adequate amount of nitrogen, supplied naturally by a nitrogen fixation process in a nitrogen cycle. However, in most cases, the increased use of fertilizers for soil rehabilitation in agriculture increases soil nitrogen concentration which exceeds the usable nitrogen composition of the soil. While the extra nitrogen concentration in the soil is attractive for agriculture, it impacts the nitrogen balance of the ecosystem. Therefore, plants are left to take up and store the excess soil nitrogen, thereby making them less ideal biomass feedstock for energy production. The nitrogen content of most wood samples evaluated was below the maximum allowable limits of 0.3%, except for those of the Bugweed (0.4% N), Opepe (0.37 % N) and the African oil bean (0.4% N). Despite the slightly greater composition of nitrogen in these samples, their nitrogen compositions were still comparably much lower than those of coals.

The ash content is a key factor in selecting any solid fuel as a feedstock for thermochemical processes because its deposition is known to accelerate the corrosion of internal reactor components. During thermochemical processes such as combustion, gasification and pyro-gasification, biomass and coal deposits of ash residue layers containing reaction-inhibiting silicone particles on the char surface. These layers of ash block the char pores and inhibit the free transfer of hot oxidizing gases into the inner carbon particles. This phenomenon minimizes the rate of char partial oxidation and conversion of the inner carbon particles [33–

35]. Therefore, char oxidation rates and gasifier temperature are reduced [4, 57]. Operational issues such as the deactivation of catalysts due to fouling by ash, agglomeration due to the low melting point of biomass ash, the low conversion efficiency of the biomass, sintering, aggregation, deposition, leading to corrosion of the gasifier, may arise as a result of high amounts of ash in the feedstock [4]. Moreover, ash in high amounts reduces the calorific value of the feedstock and thus result in a reduced syngas calorific value [35–37]. It is worthy of note that high char yield does not necessarily translate to a high concentration of fixed carbon present in the char. High ash composition in the raw biomass contributes to a high yield of the intermediate char product since char is primarily made up of fixed carbon and ash particles. In such a situation, the gasification phase reactions will be greatly hindered by the huge presence of ash residue. Unlike coal, the lower ash composition of woody biomass may be insignificant if used for combustion. However, this may not be the case if considerable deposits of ash are formed during pyro-gasification.

4. Conclusion

This study evaluated the fuel properties of eight important waste wood samples as potential feedstocks for pyro-gasification. Based on previous studies reported in the literature, five key feedstock evaluators were developed to ascertain the extent to which related biomass fuel properties affect the efficiency of a pyro-gasification process and the quality of the syngas product. A hierarchy of the eight samples was established under the five evaluators: char reactivity, energy density, fuel ratio, NO_X emission, and ash deposition.

The hierarchy reveals that no individual wood species is completely efficient as feedstock for pyro-gasification. This is due to the contrasts in the fuel properties of one wood species from the other. For example, despite the low ranking of the Bugweed in the energy density evaluation, its high char reactivity to a large extent could promote the production of syngas at low temperatures. This observation highlights the importance of blending the Bugweed with wood species such as the African mesquite ranked highly for its high energy density, high fuel ratio and low ash deposition potential, but lowly in terms of char reactivity. By blending, feedstock with the right balance in fuel properties can be achieved.

Across the board, the Jacaranda was the least ranked wood species due to its low char reactivity, low energy density, low fuel ratio, high NO_X emissions, and ash deposition potentials. However, its low char reactivity may be due to its high ash content and other impurities accumulated during its handling and storage. Therefore, this necessitates the need for further studies on biomass with similar fuel properties to the Jacaranda.

This study provides relevant data in terms of ranking these wood species based on their suitability for pyro-gasification. It also provides knowledge on the criteria for blending wood species for effective pyro-gasification processes. This study paves the way for further exploration of the thermochemical conversion of various waste wood species, which will further reduce the exploration of fossil fuels.

Acknowledgements

This work was financially supported by The World Academy for Sciences in collaboration with the National Research Foundation, South Africa (TWAS-NRF) (grant number: 99983).

Declaration

Funding

Funding was made available by the TWAS-NRF doctoral research grant (grant number: 99983).

Conflicts of interest/Competing interests

All authors have no conflict of interest to report.

Availability of data and material

Experimental data and material used in this study may be made available on request.

Code availability

Not applicable

Authors' contributions

N.M. Okoro: Co-conceptualization, Methodology, Software, Investigation, Validation, Formal analysis, Resources, Data curation, Writing- Original draft, Visualization.

U.M. Ikegwu: Methodology, Investigation, Formal analysis, Writing – Review & Editing, Visualization.

K.G. Harding: Co-conceptualization, Supervision, Writing - Review & Editing, Visualization, Final approval.

M.O. Daramola: Co-conceptualization, Co-supervision, Writing - Review & Editing, Visualization.

References

1. McKendry, P.: Energy production from biomass (part 1): Overview of biomass. Biosource Technol. 83, 37–46 (2001)
2. Ramachandra, T.V.; Kamakshi, G.: Centre for Ecological Sciences Indian Institute of Science Bangalore – 560012 Summary. (2005)
3. Global Bioenergy Statistics: WBA Global Bioenergy Statistics 2018. (2018)
4. Okoro, N.M., Harding, K.G., Daramola, M.O.: Pyro-gasification of Invasive Plants to Syngas. In: Valorization of Biomass to Value-Added Commodities. pp. 317–340 (2020)
5. Yang, H., Yan, R., Chen, H., Zheng, C., Lee, D.H., Uni, V., V, N.D., March, R. V, Re, V., Recei, M., September, V.: In-Depth Investigation of Biomass Pyrolysis Based on Three Major Components : Hemicellulose , Cellulose and Lignin. Energy & Fuels. 20, 388–393 (2006)
6. Ikegwu, U.M., Ozonoh, M., Daramola, M.O.: Kinetic Study of the Isothermal Degradation of Pine Sawdust during Torrefaction Process. ACS Omega. (2021). https://doi.org/10.1021/acsomega.1c00327
7. Bilgic, E., Yaman, S., Kucukbayrak, S.: Limits of variations on the structure and the fuel characteristics of sun fl ower seed shell through torrefaction. Fuel Process. Technol. 144, 197–202 (2016). https://doi.org/10.1016/j.fuproc.2016.01.006
8. Molino, A., Chianese, S., Musmarra, D.: Biomass gasification technology: The state of the art overview. J. Energy Chem. 25, 10–25 (2016). https://doi.org/10.1016/j.jechem.2015.11.005
9. Vieira, F.R., Romero Luna, C.M., Arce, G.L.A.F., Ávila, I.: Optimization of slow pyrolysis process parameters using a fixed bed reactor for biochar yield from rice husk. Biomass and Bioenergy. 132, (2020). https://doi.org/10.1016/j.biombioe.2019.105412
10. Fahmy, T.Y.A., Fahmy, Y., Mobarak, F., El-Sakhawy, M., Abou-Zeid, R.E.: Biomass pyrolysis: past, present, and future. Environ. Dev. Sustain. 22, 17–32 (2020). https://doi.org/10.1007/s10668-018-0200-5
11. Alper, K., Tekin, K., Karagöz, S., Ragauskas, A.J.: Sustainable energy and fuels from biomass: A review focusing on hydrothermal biomass processing. Sustain. Energy Fuels. 4, 4390–4414 (2020). https://doi.org/10.1039/d0se00784f
12. Mikulandric, R., Böhning, D., Lončar, D.: Modelling of Temperature and Syngas Composition in a Fixed Bed Biomass Gasifier using Nonlinear Autoregressive Networks. J. Sustain. Dev. Energy, Water Environ. Syst. 8, 145–161 (2020). https://doi.org/10.13044/j.sdewes.d7.0263
13. Molino, A., Larocca, V., Chianese, S., Musmarra, D.: Biofuels production by biomass gasification: A review. Energies. 11, 1–31 (2018). https://doi.org/10.3390/en11040811
14. Chen, Z., Wang, M., Jiang, E., Wang, D., Zhang, K., Ren, Y., Jiang, Y.: Pyrolysis of Torrefied Biomass. Trends Biotechnol. 36, 1287–1298 (2018). https://doi.org/10.1016/j.tibtech.2018.07.005
15. Anukam, A., Mamphweli, S., Okoh, O., Reddy, P.: Influence of Torrefaction on the Conversion

Efficiency of the Gasification Process of Sugarcane Bagasse. (2017). https://doi.org/10.3390/bioengineering4010022

16. Tian, Y., Li, J., Wei, W., Zong, P., Zhang, D., Zhu, Y., Qiao, Y.: Parametric effect of biomass partial hydropyrolysis process in a downer reactor to co-produce high-quality tar and syngas. Bioresour. Technol. 320, 124401 (2021). https://doi.org/10.1016/j.biortech.2020.124401

17. AlNouss, A., McKay, G., Al-Ansari, T.: Production of syngas via gasification using optimum blends of biomass. J. Clean. Prod. 242, 118499 (2020). https://doi.org/10.1016/j.jclepro.2019.118499

18. Duruaku, J.I., Ajiwe, V.I.E., Okoye, N.H., Arinze, R.U.: An Evaluation of the Calorific Values of the Branches and Stems of 11 Tropical Trees. J. Sustain. Bioenergy Syst. 6, 44–54 (2016)

19. Ayeni, A.O., Adeeyo, O.A., Oresegun, O.M., Oladimeji, E.: Compositional analysis of lignocellulosic materials : Evaluation of an economically viable method suitable for woody and non-woody biomass American Journal of Engineering Research (AJER). Am. J. Eng. Res. 4, 14–19 (2015)

20. Sluiter, a., Hames, B., Ruiz, R., Scarlata, C., Sluiter, J., Templeton, D., Crocker, D.: NREL/TP-510-42618 analytical procedure - Determination of structural carbohydrates and lignin in Biomass. (2012)

21. ASTM International: ASTM E872-82, Standard Test Method for Volatile Matter in the Analysis of Particulate Wood Fuels. , West Conshohocken, PA (2013)

22. ASTM International: ASTM E1755-01, Standard Test Method for Ash in Biomass. , West Conshohocken, PA (2015)

23. ASTM International: ASTM E1756-08, Standard Test Method for Determination of Total Solids in Biomass. , West Conshohocken, PA (2015)

24. Azubuike, C.P., Okhamafe, A.O.: Physicochemical , spectroscopic and thermal properties of microcrystalline cellulose derived from corn cobs. 1–7 (2012)

25. Eloy, E., Silva, D.A. Da, Caron, B.O., Souza, V.Q. De: Capacidade energética da madeira e da casca de acácia-negra em diferentes espaçamentos. Pesqui. Florest. Bras. 35, 163 (2015). https://doi.org/10.4336/2015.pfb.35.82.606

26. Bhuiyan, N.H., Selvaraj, G., Wei, Y., King, J.: Role of lignification in plant defense. Plant Biotechnol. 4, 158–159 (2009). https://doi.org/10.1093/jxb/ern290.8.

27. Saidur, R., Abdelaziz, E.A., Demirbas, A., Hossain, M.S., Mekhilef, S.: A review on biomass as a fuel for boilers. Renew. Sustain. Energy Rev. 15, 2262–2289 (2011). https://doi.org/10.1016/j.rser.2011.02.015

28. Wang, P., Howard, B.H.: Impact of thermal pretreatment temperatures on woody biomass chemical composition, physical properties and microstructure. Energies. 11, 1–20 (2018). https://doi.org/10.3390/en11010025

29. Yu, J., Paterson, N., Blamey, J., Millan, M.: Cellulose , xylan and lignin interactions during pyrolysis of lignocellulosic biomass. Fuel. 191, 140–149 (2017). https://doi.org/10.1016/j.fuel.2016.11.057

30. Kanwal, S., Chaudhry, N., Munir, S., Sana, H.: Effect of torrefaction conditions on the physicochemical characterization of agricultural waste (sugarcane bagasse). Waste Manag. 88,

280–290 (2019). https://doi.org/10.1016/j.wasman.2019.03.053

31. Al-Zareer, M., Dincer, I., Rosen, M.A.: Influence of selected gasification parameters on syngas composition from biomass gasification. J. Energy Resour. Technol. Trans. ASME. 140, 1–10 (2018). https://doi.org/10.1115/1.4039601

32. Barbanera, M., Muguerza, I.F.: Effect of the temperature on the spent coffee grounds torrefaction process in a continuous pilot-scale reactor. Fuel. 262, 116493 (2020). https://doi.org/10.1016/j.fuel.2019.116493

33. Aguado, R., Cuevas, M., Pérez-Villarejo, L., Martínez-Cartas, M.L., Sánchez, S.: Upgrading almond-tree pruning as a biofuel via wet torrefaction. Renew. Energy. 145, 2091–2100 (2020). https://doi.org/10.1016/j.renene.2019.07.142

34. Hernández, J.J., Lapuerta, M., Monedero, E., Pazo, A.: Biomass quality control in power plants: Technical and economical implications. Renew. Energy. 115, 908–916 (2018). https://doi.org/10.1016/j.renene.2017.09.026

35. McKendry, P.: Energy production from biomass (part 3): gasification technologies. Bioresour. Technol. 83, 55–63 (2002). https://doi.org/10.1016/S0960-8524(01)00120-1

36. Speight, J.G.: Production of syngas, synfuel, bio-oils, and biogas from coal, biomass, and opportunity fuels. Elsevier Ltd (2015)

37. Vélez, J.F., Chejne, F., Valdés, C.F., Emery, E.J., Londoño, C.A.: Co-gasification of Colombian coal and biomass in fluidized bed: An experimental study. Fuel. 88, 424–430 (2009). https://doi.org/10.1016/j.fuel.2008.10.018

38. Bryers, R.W.: Fireside slagging, fouling, and high-temperature corrosion of heat-transfer surface due to impurities in steam-raising fuels. Prog. Energy Combust. Sci. 22, 29–120 (1996). https://doi.org/10.1016/0360-1285(95)00012-7

39. Vassilev, S. V., Baxter, D., Andersen, L.K., Vassileva, C.G.: An overview of the chemical composition of biomass. Fuel. 89, 913–933 (2010). https://doi.org/10.1016/j.fuel.2009.10.022

40. Theis, M., Skrifvars, B.J., Hupa, M., Tran, H.: Fouling tendency of ash resulting from burning mixtures of biofuels. Part 1: Deposition rates. Fuel. 85, 1125–1130 (2006). https://doi.org/10.1016/j.fuel.2005.10.010

41. Demirbas, A.: Combustion characteristics of different biomass fuels. Prog. Energy Combust. Sci. 30, 219–230 (2004). https://doi.org/10.1016/j.pecs.2003.10.004

42. Vamvuka, D., Zografos, D.: Predicting the behaviour of ash from agricultural wastes during combustion. Fuel. 83, 2051–2057 (2004). https://doi.org/10.1016/j.fuel.2004.04.012

43. Cuiping, L., Chuangzhi, W., Yanyongjie, Haitao, H.: Chemical elemental characteristics of biomass fuels in China. Biomass and Bioenergy. 27, 119–130 (2004). https://doi.org/10.1016/j.biombioe.2004.01.002

44. Zevenhoven-Onderwater, M., Blomquist, J., Skrifvars, B., Backman, R., Hupa, M.: The prediction of behaviour of ashes from five different solid fuels.pdf. Fuel. 79, 1353–1361 (2000)

45. Miles, T.R., Baxter, L.L., Bryers, R.W., Jenkings, B.M., Oden, L.L.: Alkali deposits found in Biomass Power Plants: A preliminary investigation of their extent and nature. (1995)

46. Melane, M., Ham, C., Meincken, M.: Characteristics of selected non-woody invasive alien plants

in South Africa and an evaluation of their potential for electricity generation. J. Energy South. Africa. 28, 92 (2017). https://doi.org/10.17159/2413-3051/2017/v28i3a1896

47. Kumar, R., Sarkar, A., Prasad, J.: Effect of torrefaction on the physicochemical properties of eucalyptus derived biofuels : estimation of kinetic parameters and optimizing torrefaction using response surface methodology (RSM). Energy. 198, 117369 (2020). https://doi.org/10.1016/j.energy.2020.117369

48. Nhuchhen, D.R., Afzal, M.T.: HHV predicting correlations for torrefied biomass using proximate and ultimate analyses. Bioengineering. 4, (2017). https://doi.org/10.3390/bioengineering4010007

49. Channiwala, S.A., Parikh, P.P.: A unified correlation for estimating HHV of solid , liquid and gaseous fuels. Fuel. 81, 1051–1063 (2002)

50. Wolfenden, A., Jacobs, T.: Experimentation and Uncertainty Analysis for Engineers. J. Test. Eval. 19, 498–499 (1991). https://doi.org/10.1520/JTE12616J

51. John, R.T.: An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurement. University Science Books (1997)

52. Blasi, C. Di: Dynamic behaviour of strati " ed downdraft gasi " ers. 55, (2000)

53. Dogru, M.: Gasification of hazelnut shells in a downdraft gasifier. 27, 415–427 (2002)

54. Mitchual, S.J., Frimpong-mensah, K., Darkwa, N.A.: Evaluation of Fuel Properties of Six Tropical Hardwood Timber Species for Briquettes. J. Sustain. Bioenergy Syst. 4, 1–9 (2014). https://doi.org/10.4236/jsbs.2014.41001

55. Sikarwar, S., Zhao, M., Fennell, P., Shah, N., Anthony, E.: Progress in biofuel production from gasification. Prog. Energy Combust. Sci. 61, 189–248 (2017). https://doi.org/10.1016/j.pecs.2017.04.001

56. Chen, Z., Zhu, Q., Wang, X., Xiao, B., Liu, S.: Pyrolysis behaviors and kinetic studies on Eucalyptus residues using thermogravimetric analysis. Energy Convers. Manag. 105, 251–259 (2015). https://doi.org/10.1016/j.enconman.2015.07.077

57. Jayanti, S., Maheswaran, K., Saravanan, V.: Assessment of the effect of high ash content in pulverized coal combustion. Appl. Math. Model. 31, 934–953 (2007). https://doi.org/10.1016/j.apm.2006.03.022