# Characteristics of potential gasifier fuels in selected regions of the Lake Victoria Basin

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All countries in the Lake Victoria Basin depend mostly on hydroelectric power for the provision of energy. Gasification technology has a high potential for reducing biomass energy consumption whilst increasing access to modern energy services. The key aspect for the failure of gasification operations in the Lake Victoria Basin is inadequate adaptation of gasification equipment to fuel characteristics, lack of fuel specification and inappropriate material choice. We therefore investigated the thermo-chemical characterisation of six biomass fuels, namely *Pinus caribaea*, *Calitris robusta*, *Cupressus lusitanica*, *Eucalyptus grandis, Pinus patula* and sugarcane bagasse from selected regions of the Lake Victoria Basin. Ultimate analysis was done using a Flash 2000 elemental analyser. Moisture content, ash content and volatile matter were determined in oven and muffle furnaces while heating values were determined using a Gallenkamp calorimeter. The mean percentage levels obtained indicate that all six biomass fuels had a mean range for nitrogen of 0.07±0.2–0.25±0.07%, for carbon of 40.45±0.61–48.88±0.29%, for hydrogen of 4.32±0.13–5.59±0.18% and for oxygen of 43.41±1.58–51.1±0.64%. Moisture content ranged between 25.74±1.54% and 56.69±0.52%, ash content between 0.38±0.02% and 2.94±0.14%, volatile matter between 74.68±0.49% and 82.71±0.19% and fixed carbon between 14.35±0.33% and 24.74±0.27%. Heating values ranged between 16.95±0.10 MJ/kg and 19.48±0.42 MJ/kg. The results suggest that all six biomass fuels are potential biomass gasification materials.

## Introduction

Modern energy, such as electricity, is crucial in order to achieve the Millennium Development Goals of poverty reduction, improved education and environmental sustainability.[1] Currently, about one-third of the world's population, or two billion people, have only intermittent access to modern energy services. The energy sector in the Lake Victoria Basin is dominated by traditional biomass-based fuels, which contribute over 70% to the total energy consumption.[2,3] As a result of the use of poor technology (e.g. three stones and charcoal stoves), many regard biomass energy as inferior. Women and children inhale fumes while cooking indoors and spend considerable time collecting firewood.[2,4,5] Hydroelectric power and energy from petroleum products is prohibitively expensive and mostly restricted to urban areas. In order to alleviate poverty in the Lake Victoria Basin, the rural-based households (over 80%) will need access to modern energy services.[2]

Biomass in the form of trees, shrubs, agro and forest wastes, grasses and vegetables is abundant in the Lake Victoria Basin and is renewable. Fortunately, the basin is located on the equator and as a result of this proximity receives an abundant insolation averaging 4.5 kWh/m$^2$/day.[6] This insolation provides the necessary conducive environment for vast growth of biomass. What is really required to increase rural household energy security is to catalyse rural industrialisation. Biomass gasification for energy production is one such system.[7,8] Gasification technology involves incomplete combustion of biomass resulting in the production of combustible gases consisting of carbon monoxide, hydrogen and traces of methane.[8-12] Gasification is the most efficient way known to date of converting biomass into energy; it converts 60–90% of the energy in the biomass into energy in the gas, compared to traditional systems which utilise 10–30%.[13,14]

## Method and materials

### *Study area*

Biomass samples were obtained from the forests located in the Lake Victoria Basin in Kenya and Uganda. In Kenya, eight regions were chosen: Malava Forest in Kakamega County, Kibiri Block Forest in Vihiga County, Ombo Forest in Migori County, Kodera Forest in Rachuonyo County, Kakamega Forest in Kakamega County, Port Victoria natural forest in Busia County, Aloso Block Forest in Migori County and Sony Sugar Company in Migori County. In Uganda, samples were obtained from the Wakiso District. These forests were purposely selected because they are managed by forest services in both Kenya and Uganda.

### *Sampling procedure and collection*

Breast-height (1.3 m from the ground) stem wood samples were collected from each species. *Cupressus lusitanica* was collected from Kakamega, Ombo, Kodera and Port Victoria Forests, *Pinus patula* was collected from Kibiri and Kodera Forests, *Pinus caribaea* from Kodera (Kenya) and Wakiso (Uganda) Forests, *Calitris robusta* from Aloso Forest and *Eucalyptus grandis* from Wakiso Forest. The samples were cut into small wood chips. Sugarcane bagasse was collected from the Sony Sugar Company and was sampled from the top, middle and bottom of the heap of sugarcane bagasse. The sugarcane bagasse samples were subsequently placed in three 50-kg gunny sacks and transported for analysis.

### Determination of moisture content

Moisture content was determined in accordance with ASTM Standard D3173-87.[15] Nine replicates were obtained from each biomass sample. The sample was placed in a convection oven at 105±3 °C for 4 h, removed and cooled to room temperature in desiccators with $P_2O_5$ as the drying agent. The dish containing the oven-dried sample was weighed and the weight recorded. The sample was placed back into the convection oven at 105±3 °C and dried to constant weight. Percentage weight loss was taken as the moisture content of the original sample.

### Ash determination

Ash determination was done in accordance with ASTM Standard D3174-97.[16] The nine dried samples (10 g) were placed into crucibles and placed in a furnace set to 575±25 °C for 4 h, after which the crucibles containing the samples were removed and cooled in desiccators. The weight of the crucible and the sample was then recorded to the nearest 0.1 mg. The ash content (%) was calculated as:

$$\text{Ash} = \frac{W_3 - W_1}{W_2 - W_1} \times 100 \qquad \text{Equation 1}$$

where $W_1$ is the mass of the empty dry crucible, $W_2$ is the mass of the dry crucible plus the dry sample of biomass and $W_3$ is the mass of the dry crucible plus the cooled greyish-white ash.

### Volatile matter determination

Determination of volatile matter content was done in accordance with ASTM standards.[17] Approximately 10 g of the dried sample was weighed into crucibles with a closely fitting cover and placed into a muffle furnace maintained at 950±20 °C. After 7 min of heating, the crucibles were removed, cooled in desiccators and weighed. Nine samples of each feedstock were used. Volatile matter (%) was calculated as:

$$\text{Volatile matter} = 100 \times (I - F)/I, \qquad \text{Equation 2}$$

where I is the initial weight of the sample (g) and F is the final weight of the sample (g).

### Calculation of percentage fixed carbon

Fixed carbon was calculated using the volatile matter and ash amount according to McKendry[18] as follows:

$$\%\,FC = 100 - (\%\,VM + \%\,\text{ash}), \qquad \text{Equation 3}$$

where FC is the fixed carbon and VM is volatile matter.

### Energy content

The energy content was determined in accordance with ASTM Standard D2015-96.[19] A Gallenkamp auto bomb calorimeter (model number SG97/10/070, Fistreem International Limited, Leicestershire, UK) was used.

### Higher heating values derived from theoretical equations

Equations 4–6 were used to estimate the higher heating values (HHV) of the biomass samples and the results were compared with the experimental values.

$$HHV = 0.196 \times FC + 14.119 \qquad \text{Equation 4}^{20}$$

$$HHV = 0.4373 \times C - 1.6701 \qquad \text{Equation 5}^{21}$$

$$HHV = -0.763 + 0.301 \times C + 0.525 \times H + 0.064 \times O \qquad \text{Equation 6}^{22}$$

### Ultimate analysis

The carbon, nitrogen and hydrogen contents were determined using a Flash 2000 elemental analyser (model number 31712052, Thermo Fisher Scientific, Delft, the Netherlands) according to ASTM Standard E775.[23]

### Calculations for synthesis gas composition

Equations 7–9 developed by Gopal[24] were used to predict the percentage volume of CO, $CO_2$, and $H_2$:

### Data analysis

Data were subjected to statistical analyses including a one-way analysis of variance (ANOVA) and Student-Newman-Keuls (SNK) test. These methods are useful in providing interdependence of the variables and significant differences.[25]

## Results and discussion

### Proximate analysis

A summary of the proximate analysis is presented in Table 1.

Table 1 shows that the moisture contents of the six biomass samples were significantly different ($p<0.05$, SNK test). The moisture content of wood typically varies between 10% and 60% while that of sugarcane bagasse ranges between 40% and 60%.[26,27] In this study, the moisture contents of *Pinus caribaea, Calitris robusta, Cupressus lusitanica, Eucalyptus grandis* and *Pinus patula* were in the range of 10–60%. The moisture content of sugarcane bagasse was in the range of 40–60%. Brammer and Bridgewater[28] reported that a moisture content of up to 20% and 50% is acceptable for downdraught and updraught gasifiers,

**Table 1:** Proximate analysis of the biomass fuels

| Fuel type | % Moisture | % Ash content | % Volatile matter | % Fixed carbon |
|---|---|---|---|---|
| *Pinus caribaea* | $56.69 \pm 0.32^{d}$ | $0.38 \pm 0.02^{a}$ | $76.98 \pm 0.61^{b}$ | $22.64 \pm 0.63^{d}$ |
| *Calitris robusta* | $48.64 \pm 0.28^{c}$ | $0.54 \pm 0.02^{a}$ | $78.79 \pm 0.61^{b}$ | $20.67 \pm 0.63^{b}$ |
| *Cupressus lusitanica* | $39.11 \pm 3.24^{b}$ | $0.58 \pm 0.05^{a}$ | $74.68 \pm 0.49^{a}$ | $24.74 \pm 0.54^{e}$ |
| *Eucalyptus grandis* | $48.59 \pm 0.43^{c}$ | $0.42 \pm 0.02^{a}$ | $78.24 \pm 0.25^{b}$ | $21.34 \pm 0.27^{bc}$ |
| *Pinus patula* | $25.74 \pm 1.54^{a}$ | $0.39 \pm 0.05^{a}$ | $77.57 \pm 0.23^{b}$ | $22.04 \pm 0.28^{cd}$ |
| Sugarcane bagasse | $36.47 \pm 0.32^{b}$ | $2.94 \pm 0.14^{b}$ | $77.57 \pm 0.23^{b}$ | $14.35 \pm 0.33^{a}$ |
| *p*-value | < 0.0001 | < 0.0001 | < 0.0001 | <0.001 |

*Values shown are mean±s.e.,* n=9.

*Mean values followed by the same small letter(s) within the same column are not significantly different from one another (one-way ANOVA, SNK test, $\alpha=0.05$).*

respectively, whereas fluidised bed gasifiers have been reported to gasify materials with moisture contents of up to 70%.[29]

Sugarcane bagasse showed significantly higher levels of ash compared with *Pinus caribaea, Calitris robusta, Cupressus lusitanica, Eucalyptus grandis* and *Pinus patula*. All six biomass feedstocks qualified for use in biomass gasification as they had an ash content less than 5%.[30] All the biomass feedstocks investigated can be used in downdraught gasifiers as they contained less than 6% ash[31,32] and sugarcane bagasse can be used in updraught gasifiers as the minimum ash content was 1.4% and the maximum was 25%.[31,32]

Sugarcane bagasse had a higher percentage mean of volatile matter than did *Cupressus lusitanica*. The percentage of volatile matter of *Pinus caribaea, Calitris robusta, Eucalyptus grandis* and *Pinus patula* did not differ significantly from one another ($p > 0.05$, SNK test). Woods typically have a volatile matter of 72–78%.[33,34]

*Cupressus lusitanica* had a higher fixed carbon content than sugarcane bagasse. Sugarcane bagasse had the lowest fixed carbon content. The fixed carbon contents of *Pinus caribaea* and *Pinus patula* did not differ statistically ($p > 0.05$, SNK test). According to McKendry[18], wood has a fixed carbon content of about 20%. Anjireddy and Sastry[35] showed that sugarcane bagasse had a fixed carbon content of 15.8%.

## Ultimate analysis

A summary of the ultimate analyses is presented in Table 2.

Table 2 shows the percentage weight of nitrogen of the six biomass feedstocks; the mean percentages of nitrogen did not differ significantly ($p > 0.05$, SNK test). According to Jenkins et al.[36], all biomass material contains 0.2–1% nitrogen. To avoid corrosion and emission of $NO_x$ to the atmosphere during combustion, according to Obernberger et al.[37], all biomass material must contain less than 0.6% nitrogen. Our six biomass samples contained less than 0.6% nitrogen, which qualifies them as suitable feedstock for gasification processes.

There was a significant difference in the percentage weight of carbon among the six biomass fuels ($p < 0.05$, SNK test). The percentage mean carbon contents of *Cupressus lusitanica*, *Calitris robusta* and *Pinus patula* were significantly higher than that of sugarcane bagasse. According to Demirbas[13] and BTG[38], the carbon content of typical biomass must range from 42% to 54%. The six biomass fuels were within this range.

Table 2 shows the percentage weight of hydrogen of the six biomass samples. The hydrogen contents of *Pinus caribaea*, *Calitris robusta*, *Cupressus lusitanica*, *Eucalyptus grandis* and *Pinus patula* were not significantly different from one another, but sugarcane bagasse had a significantly lower percentage of hydrogen ($p < 0.05$, SNK test).

Turn et al.[39] reported 4.98% hydrogen for bagasse and Cheremisnoff[40] found that typical woods have about 6% hydrogen. BTG[38] reported hydrogen in the range of 5.5–6.2%. These reports are in agreement with our results.

The mean percentage oxygen of *Pinus caribaea, Eucalyptus grandis* and sugarcane bagasse were significantly higher than that of *Pinus patula* ($p < 0.05$, SNK test; Table 2). The mean percentage oxygen of *Calitris robusta* and *Cupressus lusitanica* was not significantly different ($p > 0.05$, SNK test). Raveendran et al.[41] reported an oxygen percentage

**Table 2:** Ultimate analysis of the biomass fuels

| Fuel type | % Nitrogen | % Carbon | % Hydrogen | % Oxygen |
|---|---|---|---|---|
| *Pinus caribaea* | 0.25±0.07 | 45.57±0.26 | 5.44±0.22$^{b}$ | 48.36±0.35$^{c}$ |
| *Calitris robusta* | 0.18±0.01 | 47.26±0.21$^{bc}$ | 5.56±0.17$^{b}$ | 46.46±0.27$^{b}$ |
| *Cupressus lusitanica* | 0.07±0.02 | 48.88±0.29$^{c}$ | 5.17±0.34$^{b}$ | 45.46±0.45$^{b}$ |
| *Eucalyptus grandis* | 0.17±0.02 | 45.50±0.35$^{b}$ | 5.55±0.13$^{b}$ | 48.39±0.37$^{c}$ |
| *Pinus patula* | 0.22±0.04 | 47.84±1.57$^{bc}$ | 5.59±0.18$^{b}$ | 43.41±1.58$^{a}$ |
| Sugarcane bagasse | 0.23±0.04 | 40.45±0.61$^{a}$ | 4.32±0.13$^{a}$ | 51.1±0.64$^{c}$ |
| *p*-value | < 0.056 | < 0.0001 | < 0.0003 | < 0.001 |

*Values shown are mean±s.e.,* n=*9.*
*Mean values followed by the same small letter(s) within the same column are not significantly different from one another (one-way ANOVA, SNK test, $\alpha$=0.05).*

**Table 3:** The energy content of the biomass fuels

| Fuel type | Measured heat value (MJ/kg) | Predicted higher heating value (MJ/kg) | | |
|---|---|---|---|---|
| | | Demirbas[20] | Tilman[21] | Jenkins and Ebeling[22] |
| *Pinus caribaea* | 18.61±0.12$^{b}$ | 18.56±0.52$^{b}$ | 18.26±0.11$^{b}$ | 18.93±0.12$^{b}$ |
| *Calitris robusta* | 18.39±0.08$^{b}$ | 18.17±0.55$^{b}$ | 18.99±0.09$^{c}$ | 19.39±0.11$^{b}$ |
| *Cupressus lusitanica* | 17.44±0.04$^{a}$ | 18.97±0.41$^{b}$ | 19.70±0.13$^{c}$ | 19.60±0.16$^{b}$ |
| *Eucalyptus grandis* | 19.13±0.13$^{c}$ | 18.30±0.23$^{b}$ | 18.23±0.15$^{c}$ | 18.97±0.09$^{b}$ |
| *Pinus patula* | 19.48±0.42$^{c}$ | 18.44±0.23$^{b}$ | 19.25±0.69$^{c}$ | 19.54±0.41$^{b}$ |
| Sugarcane bagasse | 16.95±0.10$^{a}$ | 16.93±0.39$^{a}$ | 16.02±0.26$^{a}$ | 17.20±0.17$^{a}$ |
| *p*-value | < 0.0001 | < 0.001 | < 0.001 | < 0.001 |

*Values shown are mean±s.e.,* n=*9.*
*Mean values followed by the same small letter(s) within the same column are not significantly different from one another (one-way ANOVA, SNK test, $\alpha$=0.05).*

of 47.1%, which is similar to our results. BTG[38] showed that typical biomass materials have an oxygen percentage of 40–51%. The results from this study therefore are in agreement with those of previous studies.

## *Heating values*

The energy content of the biomass feedstocks is presented in Table 3.

Table 3 shows a significant difference in the energy contents of the six biomass fuels ($p<0.05$, SNK test). *Pinus patula* and *Cupressus lusitanica* had higher energy contents than *Eucalyptus grandis* and sugarcane bagasse. The energy contents of *Pinus caribaea* and *Calitris robusta* did not differ significantly. Nonde[42] reported heating values of wood fuels of between 18 MJ/kg and 20 MJ/kg. Howlett and Gamache[43] also reported values of 17.7–21.0 MJ/kg for foliage materials. These values are within the range of our results. The measured heating values were also in agreement with the predicted values. The heating value determines the suitability of biomass for pyrolysis, carbonisation, liquefaction and gasification. The heating value is a function of the chemical composition, in particular, the carbon content. Variation in the heating values among different species and different plant components shows differences in the chemical composition, which is used to demonstrate the quality of the fuel.

## *Predicted synthesis gas*

The predicted synthesis gas composition is presented in Table 4.

The predicted synthesis gas composition from the gasification of *Eucalyptus grandis* was 16.52±0.43% $H_2$ and 25.13±0.65% CO. These values were slightly higher than those reported by Gopal[24] who found 16.1% $H_2$ and 24.0% CO. For sugarcane bagasse, the predicted composition was 15.04±0.54% $H_2$ and 24.47±0.88% CO, which is similar to those reported by Gopal[24] who found 15.4% $H_2$ and 23.4% CO. The Energy and Resources Institute[44] found that typical biomass produces 18–22% CO and 13–19% $H_2$. Sharma[45] concluded that feedstocks which produced 15% CO and 13% $H_2$ were considered acceptable for gasification.

Table 5 gives a comparison of selected properties of the selected biomass feedstocks in the Lake Victoria region.

*Cupressus lusitanica* from the Ombo Forest had a higher moisture content than that from the Kodera Forest ($p<0.05$, *t*-test). *Pinus patula* from the Kodera Forest had a higher moisture content than that from the Kibiri Forest. *Cupressus lusitanica* from the Kakamega Forest had a significantly higher percentage of nitrogen than that from the Kodera, Ombo and Port Victoria Forests ($p<0.05$, SNK test). There was no significant difference in the percentage of nitrogen in *Pinus caribaea* from the Kodera and Wakiso Forests ($p>0.05$, *t*-test). This variation in the percentage of nitrogen among the regions and species is mainly because of differences in environmental factors, nutrients and water.[46]

There also were significant differences in the percentage of carbon in *Cupressus lusitanica* ($p<0.04$, SNK test). The percentage of carbon in *Cupressus lusitanica* from the Kakamega, Ombo and Port Victoria

**Table 4:** The predicted synthesis gas composition of the biomass fuels

| Biomass fuel | % $CO_2$ | % $H_2$ | % CO |
|---|---|---|---|
| *Pinus caribaea* | 11.03±0.10 | 16.42±0.68 | 25.31±1.05 |
| *Calitris robusta* | 10.42±0.08 | 16.29±0.51 | 25.45±0.80 |
| *Cupressus lusitanica* | 9.79±0.11 | 15.92±1.06 | 26.66±1.78 |
| *Eucalyptus grandis* | 11.06±0.12 | 16.52±0.43 | 25.13±0.65 |
| *Pinus patula* | 10.30±0.51 | 15.43±0.91 | 24.39±1.43 |
| Sugarcane bagasse | 13.02±0.26 | 15.04±0.54 | 24.47±0.88 |

*Values shown are mean±s.e.,* n=*9.*

**Table 5:** Comparison of selected properties of the biomass from different regions within the Lake Victoria Basin

| Species | Region | % Moisture | % Nitrogen | % Carbon | % Hydrogen |
|---|---|---|---|---|---|
| *Cupressus lusitanica* | Ombo | 47.95±0.25 | $0.05\pm0.03^{a}$ | $49.99\pm0.39^{b}$ | $5.73\pm0.26^{b}$ |
| | Kodera | 34.69±4.54 | $0.02\pm0.01^{a}$ | $47.96\pm0.75^{a}$ | $6.56\pm0.29^{b}$ |
| | Kakamega | | $0.16\pm0.00^{b}$ | $49.09\pm0.16^{ab}$ | $4.28\pm0.33^{a}$ |
| | Port Victoria | | $0.04\pm0.01^{a}$ | $48.46\pm0.00^{ab}$ | $4.11\pm0.49^{a}$ |
| | | ***p*=0.01** | ***p*=0.01** | ***p*=0.048** | ***p*=0.003** |
| *Pinus patula* | Kibiri | 23.20±0.12(0.006) | 0.05±0.00 | 46.81±0.43 | 5.18±0.31 |
| | Kodera | 30.85±2.28 | 0.31±0.02 | 45.26±0.23 | 5.80±0.18 |
| | | ***p*=0.006** | ***p*<0.0001** | ***p*=0.283** | ***p*=0.111** |
| *Pinus caribaea* | Kodera | | 0.16±0.04 | 46.81±0.43 | 5.67±0.09 |
| | Wakiso | | 0.27±0.08 | 45.26±0.23 | 5.38±0.28 |
| | | | ***p*=0.516** | ***p*=0.009** | ***p*=0.622** |

*Mean values followed by the same small letter(s) within the same column are not significantly different from one another (one-way ANOVA, SNK test, $\alpha$=0.05).*

Forests was significantly higher than that from the Kodera Forest. There was also a significant difference in the percentage of carbon in *Pinus caribaea* from Kodera and Wakiso Forests ($p < 0.05$, *t*-test). The differences in the percentage of carbon among different regions can be attributed to soil physiology.[46] The percentage of hydrogen in *Cupressus lusitanica* from Kodera and Ombo Forests was significantly higher than those from Kakamega and Port Victoria Forests ($p < 0.05$, SNK test).

## Conclusion and recommendations

The six biomass fuels had low ash content, low nitrogen content and high energy content and are therefore suitable for gasification. Significant variations were also observed in the selected thermo-chemical properties of the biomass from different regions within the Lake Victoria Basin. The predicted synthesis gas composition of the biomass fuels was more than 15% CO and 13% $H_2$. It is recommended that an actual gasification can be carried out to compare the amount of synthesis gas generated with that estimated from the thermodynamic equilibrium model.

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## Authors' contributions

G.O.M. wrote the manuscript; C.O.O. was the project leader; P.M., S.B.T., S.B. and R.B.J. collected the samples for analysis.

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