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Thermal characterization of Uganda's *Acacia hockii*, *Combretum molle*, *Eucalyptus grandis* and *Terminalia glaucescens* for gasification

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ABSTRACT

In this paper, thermal characterization of four Ugandan woody biomass species was carried out in order to ascertain their suitability for gasification for small-scale biopower generation. The analyses and tests covered the aspects of proximate analysis, ultimate analysis, heating value, Thermogravimetric Analyses (TGA), ash melting and chemical composition. *Eucalyptus grandis* revealed ideal properties that make it the most promising wood specie for gasification applications. Furthermore, the low ash content in *E. grandis* significantly minimizes the possibilities of ash deposits on the gasifier and heat exchanger surfaces. The high fixed carbon in *Terminalia glaucescens*, *Acacia hockii* and *Combretum molle* makes these species ideal for charcoal making (pyrolysis). Due to high ash melting temperatures demonstrated by these samples, their pyrolysis and gasification can therefore take place with minimal worry of the ash related problems.

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1. Introduction

Uganda has one of the highest bioenergy potential in the world [1]. Nearly 90% of the total energy needs of Ugandans are supplied by woody biomass and only 1% comes from electricity [2]. Small-scale biopower generation has not gained the much coveted popularity in Uganda despite the vast opportunities that exist. The reason for the slow penetration is partly due to the appropriate conversion technology not well developed and customized to Ugandan needs. The few available imported equipment designs assume fuel characteristics of foreign feedstock or of the country of the technology origin. There are a number of biomass projects coming up in Uganda in the foreseeable future and all these require reliable fuel characteristics to back the choice of the

conversion technology for specific local feedstocks. A number of researchers at Makerere University (Uganda) have characterized the non-woody biomass feedstock for electricity generation [3]. In this study, the focus is on characterizing the woody biomass feedstock. The parameters obtained can then form part of the inputs in designing a small-scale CHP system based on steam gasification and indirectly fired micro gas turbine for rural electrification.

Various options suitable for providing electricity to rural communities in Uganda have been compared and it was concluded that distributed small-scale biopower creates the most economic opportunities within the communities [4]. Woody biomass feedstock has an edge over non-woody biomass when used in gasification. It is important to note that historically the woody biomass supply has been from

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natural forest around the country. But these natural forests are diminishing due to population pressure and agricultural clearing. The remainder is protected rainforest. Therefore sustainability of wood fuel supply for power generation can be addressed through various interventions such as putting in place a community program for planting fast growing woody biomass (short rotation coppice) such as *Eucalyptus grandis* in the marginal agricultural land unsuitable for food production or even growing a portion of woody crops in the productive land alongside the food crops can contribute to sustained supply of woody feedstock. In the case of Uganda, it is estimated that sufficient biopower production to cover basic community electricity services would require only 300 m² caput⁻¹ or 4% of the available productive land [4]. Furthermore, promoting the use of improved wood stoves alongside the electricity generation option in order to save on the wood fuel consumed in the current domestic cook stoves would be useful in conserving the available biomass resource base. Electricity provision to the community can motivate households to conserve wood fuel which they can sell to the power plant at a good price. In order to facilitate the above developments, it is necessary to determine the most suitable woody biomass species such that intending community or business ventures have reference data to aid decision making. In this paper, results of the thermal characterization of the four Ugandan woody biomass species are presented. The objective of the study was to establish their thermal properties in order to ascertain their suitability for gasification for small-scale biopower generation. The characterization of the studied fuels covered the aspects of proximate analysis, ultimate analysis, heating value measurement, Thermogravimetric Analyses (TGA), ash melting tests and chemical composition analysis. The study was motivated by the fact that different biomass feedstocks give different degradation trends during gasification. Since gasification falls somewhere between pyrolysis and combustion, the study of pyrolysis and combustion behavior using TGA gives insights on the gasification characteristics of different biomass feedstock. In addition, knowledge about ash-softening and ash-fusion temperatures as well as chemical composition of ash is important in order to plan for ash related problems associated with biomass gasification. These include sintering, agglomeration, deposition, erosion and corrosion due to low melting point of ash in biomass feedstock [5].

2. Samples and methods

2.1. Sample definition

Like in most tropical and developing countries, woody biomass remains a major source of fuel for the majority of the households and for industrial heating applications in Uganda. Working with other national stakeholders, the authors selected the woody biomass species commonly grown for domestic and commercial fuelwood. The common woody biomass species selected for thermochemical conversion processes in this study included *E. grandis*, *Terminalia glaucescens*, *Acacia hockii* and *C. Molle*. The species were identified by a wood technologist from the Department of Forestry at

Makerere University. *E. grandis* was obtained from plantations in western part of Uganda and *T. glaucescens*, *A. hockii* and *C. Molle* were obtained from the central part of Uganda. Specifically, the species of juvenile wood with age estimate of 10–20 years were obtained from the districts of Kabarole (approx. 0.6 °N, 30.3 °E) and Nakasongola (approx. 1.33 °N, 32.5 °E) during the month of July 2010. The part of the wood sampled was pure stem with bark which was cut into wood chips. These species had been dried in the open fields for a period of 2–3 weeks at the time of sample collection. The samples were kept indoor in a closed bag to avoid contamination prior to carrying out the tests. The moisture content of samples at the time of collection was not expected to significantly differ from the moisture content measured before carrying out the tests since the samples were collected when dry, kept indoor and in a closed bag.

The purpose of characterizing these samples was to know basic fuel properties (such as moisture content, elemental composition, ash behavior, thermal decomposition behavior), which are essential in the design of commercial small-scale CHP systems based on gasification of woody biomass for Ugandan situation.

2.2. Sample preparations

The samples were taken to the Energy Laboratory at the Norwegian University of Science and Technology (NTNU), Norway where the tests and analyses were carried out. The samples were milled to powder and sieved to a particle size less than 1 mm before carrying out the tests.

2.3. Moisture content

Moisture content was determined using the ASTM E871 standard; in which three samples of each specie weighing 50 g were put in an open crucible and then placed in an oven at 105 °C, with holding time of over 24 h. The sample was removed and weighed for weight loss which represents moisture content in the fuel sample. The dry samples were then kept in a desiccator for further thermal characterization tests.

2.4. Proximate analysis

The proximate analysis was used to determine the volatile matter, fixed carbon and ash content. Volatile matter was measured by following procedures described in ASTM standard E872. 1 g sample was placed in a closed crucible was heated in the muffle furnace up to 950 °C and held at this temperature for 7 min. The weight loss of sample represents the volatile matter. The remaining sample mass in an open crucible after volatile matter determination is returned in the muffle furnace at 600 °C and held for 4 h to burn off the fixed carbon. The final residual weight of sample represents the ash content.

2.5. Ultimate analysis

The ultimate analysis was carried out in order to determine the elemental composition of the wood species by using the Vario MACRO (Elementar). ASTM E775-8 standard was used

for determination of key sample elements. The sample was burned in a combustion chamber in oxygen atmosphere with helium as a carrier gas. The combustion gases released are CO₂, H₂O, NO, NO₂, SO₂, SO₃ and N₂. SO₃, NO and NO₂ were reduced at copper contact to SO₂ and N₂. H₂O, SO₂ and CO₂ were captured in different adsorption columns. N₂ was not captured by the columns and was detected first by a thermal conductivity detector (TCD). H₂O, SO₂ and CO₂ were released consecutively and sent to the TCD. Mass percentage was then determined integrally. From the known sample weight, the C, H, N and S content was determined.

2.6. Heating value

The determination of the heating value of the samples is important in establishing the energy content per unit mass of the fuel during thermochemical conversion. The higher heating value of the samples was measured using an IKA Laboratechnik C5000 control bomb calorimeter. Samples weighing 400–600 mg were placed in the bomb calorimeter and subjected to complete combustion in an adiabatic environment. The Higher Heating Value (HHV) was calculated from measured temperature increase in the adiabatic system.

2.7. Ash melting and chemical composition

In general, ash that is high in silica and/or alumina will have high ash melting points, but this can be reduced by the presence of both iron and calcium. The major difference between biomass and coal ashes is that for the majority of most biomasses the ash consists mainly of salts. Most of the biomass ash consists of potassium, calcium, phosphorus, and, further, sodium, magnesium, iron, silicon, and trace elements. As a result biomass ashes have low ash melting points of, for example, 800 °C for some straws [6]. Potassium is often organically bound in biomass which will vaporize and decompose during combustion and will form oxides, hydroxides, chlorides and sulfates. These are low melting species and condense on walls, tubes and fly-ash particles causing slagging and fouling [7].

To begin the experiment, the ash samples produced at 550 °C were shaped into cubic specimens of dimensions approximating to 5 mm in height and diameter. Then the cubic specimens were heated in an oven with a heating rate of 6 °C min⁻¹ from the room temperature to 1500 °C. Through a high temperature precision camera at one end of the furnace tube, the shape of the samples in the tube was recorded and evaluated accordingly. The temperature at which the characteristic changes of shape (i.e. initial deformation/sintering, softening, hemisphere and flow/fluid) occur was recorded.

For ash composition, the samples were sent to ALS Laboratory Group Norway AS for analysis. Determination of Cl-total was by EPA method 200.8 (modified). Digestion was done by sintering at 550 °C with Na₂CO₃ + ZnO, digestion with water and cleaning with cation exchanger. Detection and quantification was by ICP-SFMS standard. Determination of metals (MG-2) was by EPA method (modified) 200.7 (ICP-AES) and 200.8 (ICP-SFMS). Pre-treatment involved dry weight determination performed at 105 °C according to Swedish standard SS 028113. This was followed by digestion to

determine As, Cd, Co, Cu, Hg, Ni, Pb, S and Zn in which the sample was dried at 50 °C and dissolved in HNO₃/HCl/HF in closed Teflon vessel in a microwave oven according to ASTM 3683. The values were corrected to dry weight at 105 °C. Other metals were determined after fusion with LiBO₂ followed by dissolution in diluted HNO₃ 1:1 according to ASTM 3682.

2.8. Thermogravimetric Analyses (TGA) experiments

STA 600 Thermogravimetric analyzer (TA instrument) was used for both pyrolysis and combustion analysis. Before the analysis, all samples were milled and grinded to less than 1 mm 10 mg sample was loaded into an alumina crucible and heated at programmed temperature. The sample was held at 25 °C for 30 min to get the balance stable. The temperature was then increased at a heating rate of 10 °C min⁻¹ up to 1000 °C and held for 10 min. The derivative weight and weight percent loss were recorded.

3. Results and discussion

A summary of the thermal properties of *E. grandis*, *T. glaucescens*, *A. hockii* and *Combretum molle* obtained are given in Table 1.

While some of the results are within the range of those commonly found with fuelwood elsewhere, some unique results were obtained as explained in the following sections.

3.1. Moisture content

The water mass fraction w_{H_2O} was in a narrow range of 9%–11.

3.2. Proximate analysis

It was very low at 0.1% for *E. grandis*. *E. grandis* has the highest volatile matter which makes it an ideal gasification feedstock. Furthermore, the low ash content in *E. grandis* significantly minimizes the possibilities of ash deposits on the gasifier and heat exchanger surfaces. The high fixed carbon in *T. glaucescens*, *A. hockii* and *C. molle* makes these species ideal for charcoal making (pyrolysis).

3.3. Ultimate analysis

The nitrogen content of the species was found to be very low implying that the danger of fuel NO_x formation during thermochemical conversion is minimal. *E. grandis* gave the lowest amount of nitrogen at 0.11% which makes it suitable for gasification even at elevated temperatures (800 °C–1200 °C) with negligible effect of NO_x. Any possibility of thermal NO_x formation would normally occur when the temperature are close to 1300 °C, which is far beyond the achievable temperature in small-scale biomass combustors. Furthermore the gasification study on these species will consider using steam as a gasifying medium in order to limit the nitrogen dilution of syngas associated with air gasification. The sulfur content was also very low for all samples, which minimizes SO_x emissions to the atmosphere during thermochemical conversion of the feedstock that in turn would lead to acid rain formation.

Table 1 – Thermal properties of *E. grandis*, *T. glaucescens*, *A. hockii* and *C. molle*.

| Property | | <i>E. grandis</i> | <i>T. glaucescens</i> | <i>A. hockii</i> | <i>C. molle</i> | Standard deviation |
|---|------------|-------------------|-----------------------|------------------|-----------------|--------------------|
| Moisture (mass fraction %, w.b.) | | 10.9 | 10 | 10.3 | 9 | 0.687 |
| HHV (MJkg ⁻¹ , d.b.) | | 19.2 | 19.3 | 19.2 | 19.1 | 0.070 |
| Proximate Analysis (mass fraction %, d.b.) | Volatile | 88.4 | 83.9 | 83.8 | 82.6 | 2.210 |
| | Fixed C | 11.5 | 15.1 | 15.1 | 15.3 | 1.590 |
| | Ash | 0.1 | 1 | 1.1 | 2.1 | 0.708 |
| Ultimate Analysis (mass fraction %, d.b.) | C | 48.45 | 48.24 | 48.00 | 47.90 | 0.214 |
| | H | 7.52 | 7.91 | 7.20 | 7.69 | 0.259 |
| | O | 43.86 | 43.56 | 44.52 | 44.09 | 0.350 |
| | N | 0.11 | 0.24 | 0.23 | 0.27 | 0.061 |
| | S | 0.06 | 0.05 | 0.05 | 0.05 | 0.004 |
| Ash Melting temp. (°C) | Sintering | 1334 | 1312 | 1318 | 1332 | 9.274 |
| | Softening | 1450 | 1372 | 1368 | 1378 | 33.675 |
| | Hemisphere | Not detectable | 1412 | 1402 | 1494 | 41.215 |
| | Fluid | Not detectable | 1430 | 1450 | 1510 | 33.993 |

3.4. Heating value

The accuracy of the higher heating value (HHV) was further ascertained using equation (1), the formula developed by Channiwala and Parikh [8], with input data from proximate and ultimate analysis of the samples. There was no significant difference between the measured value and that derived from the equation. Due to low moisture contents of these species, their respective lower (effective) heating value (EHH) was also found to be high in the region of 17 MJ kg⁻¹ as calculated using equation (2), applicable to wooden fuels. All the samples have good heating value which makes them suitable for thermochemical conversion.

$$\text{HHV} = 34.91 * C + 117.83 * H - 10.34 * O - 1.51 * N + 10.05 * S - 2.11 * \text{Ash} [\text{MJ kg}^{-1}] \quad (1)$$

where C, H, O, N, S and ash are mass fractions obtained from proximate and ultimate analyses.

$$\text{EHV} = 19.2 - 21.64 * F [\text{MJ kg}^{-1}] \quad (2)$$

where F is the moisture content of the sample.

3.5. Ash melting and chemical composition

The ash melting test revealed the temperature at which the characteristic shapes (initial deformation/sintering, softening, hemisphere and flow/fluid) occur. The ash melting properties shown by the examined species are so unique in that the temperature far exceeds the widely reported melting temperature of biomass ash of around 800 °C. The high ash melting temperature can be explained once the chemical composition of ash is known. Since gasification generally takes place in the temperature range of 800 °C–1000 °C, it implies for these species, the bottom ash can be collected without causing melting problems such as deposition on the gasifier grate. Also the fly-ash carried with the producer gas combustor/heat exchanger cannot be deposited along the equipment surfaces since the operating temperatures do not reach the ash melting point. Due to high ash melting temperatures demonstrated by these samples, their pyrolysis

and gasification can therefore take place with minimal worry of the ash related problems.

The chemical compositions of the ash for the four samples are shown in Table 2. The constituents of ash are quite diverse, depending on the type of biomass, the type of soil and harvesting [9,10]. The results showed that all the four species contained high amounts of Ca, K, Mg, P and Si (except *A. hockii*) and to a lesser extent in Na. It is reported that high concentrations of Si, K and Na may form low melting point eutectics, which can cause slagging or bed agglomeration in combustors or gasifiers [11]. The measured Chlorine in *T. glaucescens* was an order of ten higher than for the rest of the samples. Among the species examined, *T. glaucescens* presents a greater danger to corrosion of gasifier and combustor surfaces due to its high chlorine content coupled with presence of alkali metals. Reductions in the concentrations of alkali metals and chlorine can be achieved by leaching the elements from the fuel with water [12]. The samples also contained considerable amount of other alkali minerals and micronutrients with the rest being trace elements. The ash analysis revealed that the significantly high amount of calcium detected in all the ash samples could be responsible for the white colour appearance of the ash as well as for the high ash melting temperatures. Thus the reason for the very high ash melting temperatures (>1300 °C) obtained compared to the expected biomass ash melting point (~800 °C) is due to the tenfold amount of calcium in the ash from these samples. It is well known that calcium is an inert ash forming element, which can increase ash melting temperature.

3.6. Thermogravimetric Analyses (TGA)

Fig. 1 shows the TGA curves of *A. hockii*, *C. Molle*, *E. grandis* and *T. glaucescens* during pyrolysis. *A. hockii*, *C. Molle* and *T. glaucescens* gave similar trends with overlapping curves in both weight (mass percent) loss and time derivative of the mass percent, and *E. grandis* differed in the trend with a higher peak in the rate of mass loss. The maximum rate of mass loss (derivative weight) occurred in the temperature region of 300 °C–400 °C for all species with *E. grandis* showing the highest rate of mass loss. The actual derivative weight peak

Table 2 – Ash composition for *T. glaucescens*, *C. molle*, *E. grandis* and *A. hockii*.

| Element | Unit | <i>T. glaucescens</i> | <i>C. molle</i> | <i>E. grandis</i> | <i>A. hockii</i> | Standard deviation |
|---------------|------------------------|-----------------------|-----------------|-------------------|------------------|--------------------|
| Cl | mg kg ⁻¹ | 16,800 | 1170 | 893 | 2670 | 6626.041 |
| Dry material | % | 100 | 100 | 99.8 | 99.9 | 0.083 |
| Ignition loss | % TS | 18 | 21.7 | 18.2 | 25.9 | 3.214 |
| As | mg kg ⁻¹ TS | <7 | <5 | <9 | <5 | 1.658 |
| Ba | mg kg ⁻¹ TS | 5580 | 435 | 9850 | 2120 | 3604.770 |
| Be | mg kg ⁻¹ TS | 2.87 | <0.5 | <0.6 | <0.6 | 0.998 |
| Cd | mg kg ⁻¹ TS | <0.2 | <0.1 | <0.2 | <0.1 | 0.050 |
| Co | mg kg ⁻¹ TS | 19.3 | 12.1 | 4.28 | 0.877 | 7.139 |
| Cr | mg kg ⁻¹ TS | 27.2 | 40.5 | 116 | 21.5 | 37.985 |
| Cu | mg kg ⁻¹ TS | 259 | 112 | 383 | 172 | 101.893 |
| Hg | mg kg ⁻¹ TS | <0.02 | <0.01 | <0.02 | <0.01 | 0.005 |
| Mo | mg kg ⁻¹ TS | 18.9 | 5.51 | 119 | 93.1 | 48.041 |
| Nb | mg kg ⁻¹ TS | 7.15 | <5 | 19.2 | <6 | 5.744 |
| Ni | mg kg ⁻¹ TS | 78.6 | 33.9 | 104 | 21.4 | 33.361 |
| Pb | mg kg ⁻¹ TS | 111 | 92.4 | 14.6 | 8.96 | 45.482 |
| S | mg kg ⁻¹ TS | 6800 | 3020 | 4990 | 2900 | 1601.520 |
| Sc | mg kg ⁻¹ TS | 3.25 | <1 | 2.21 | <1 | 0.940 |
| Sn | mg kg ⁻¹ TS | 1.01 | 0.486 | 1.89 | 0.332 | 0.609 |
| Sr | mg kg ⁻¹ TS | 3830 | 993 | 5870 | 3540 | 1731.97 |
| V | mg kg ⁻¹ TS | 28.6 | 8.06 | 55 | <2 | 20.730 |
| W | mg kg ⁻¹ TS | <50 | <50 | <60 | <60 | 5.000 |
| Y | mg kg ⁻¹ TS | 95.8 | 4.15 | 12.2 | 7 | 38.221 |
| Zn | mg kg ⁻¹ TS | 139 | 136 | 1160 | 125 | 444.590 |
| Zr | mg kg ⁻¹ TS | 89.4 | 27.3 | 47.1 | 2.68 | 31.758 |
| Mn | mg kg ⁻¹ TS | 7610 | 5260 | 3030 | 449 | 2652.346 |
| Si | mg kg ⁻¹ TS | 38,200 | 15,100 | 15,700 | 2080 | 12,990.139 |
| Al | mg kg ⁻¹ TS | 16,600 | 2990 | 7230 | 504 | 6131.410 |
| Ca | mg kg ⁻¹ TS | 347,000 | 335,000 | 401,000 | 299,000 | 36,588.933 |
| Fe | mg kg ⁻¹ TS | 10,100 | 2470 | 7300 | 683 | 3750.364 |
| K | mg kg ⁻¹ TS | 59,800 | 110,000 | 12,200 | 96,000 | 37,814.944 |
| Mg | mg kg ⁻¹ TS | 47,500 | 46,500 | 39,400 | 95,100 | 22,146.148 |
| Na | mg kg ⁻¹ TS | 6810 | 2540 | 10,700 | 3750 | 3153.180 |
| P | mg kg ⁻¹ TS | 11,200 | 28,300 | 39,500 | 15,600 | 11,097.860 |
| Ti | mg kg ⁻¹ TS | 1330 | 380 | 869 | 64.7 | 480.978 |

for *A. hockii*, *C. molle*, *E. grandis* and *T. glaucescens* was 10.8% min⁻¹, 9.8% min⁻¹, 13.7% min⁻¹ and 9.6% min⁻¹ respectively at an associated temperature of 360 °C. It was also within this temperature region that the weight of the samples suddenly dropped from 98% to 26% for *E. grandis* and from 96% to 30% for *A. hockii*, *C. molle* and *T. glaucescens*. This implied that for these samples, most of the devolatilization occurs in the temperature region of 300 °C–400 °C. *E. grandis* showed a unique trend with a higher rate of mass loss within a short temperature interval. The residual weight for *A. hockii*, *C. molle* and *T. glaucescens* were similar at 18% which represents the char and ash amount in the sample. The residual weight of *E. grandis* was 16.5% which also represented char and ash remaining after pyrolysis.

During combustion experiments, TGA measures the overall mass loss caused by devolatilization and burn off of the formed char. Fig. 2 shows the TGA curves of *A. hockii*, *C. molle*, *E. grandis* and *T. glaucescens* during combustion. The main combustion of all the samples (90% weight) occurred in the temperature region of 300 °C–500 °C. Still in the same temperature range, the rate of mass loss was seen to be highest. The curves also showed two oxidation zones during combustion of samples. The first oxidation zone started at close to 200 °C and died out at around 350 °C. The second oxidation zone started at around 400 °C and died out at around

500 °C. The first zone represents the devolatilization process of the sample. In the second zone, the remaining carbon in char was oxidized. *E. grandis* showed a unique trend during combustion with the highest peak experienced in the first zone and very low peak in the second zone compared to the other three species whose curves showed were closely related with similar peaks. This information shows that devolatilization takes the main stage during thermal degradation of *E. grandis*. This is consistent with all preceding tests that show *E. grandis* is rich in volatiles and exhibits excellent devolatilization properties which are essential during gasification.

3.7. Accuracy of values presented for all analyses and tests

In all the methods used in the analyses and tests, triplicates runs were made. Values presented in the manuscript are the average of triplicate results. The equipment used for various analyses and tests conforms to the highly regarded precision types and the authors were very keen in ensuring accurate calibration, precise experimental procedure, observations and analysis. Files for raw data and data sheets used in measurements can be obtained from the corresponding author when needed.

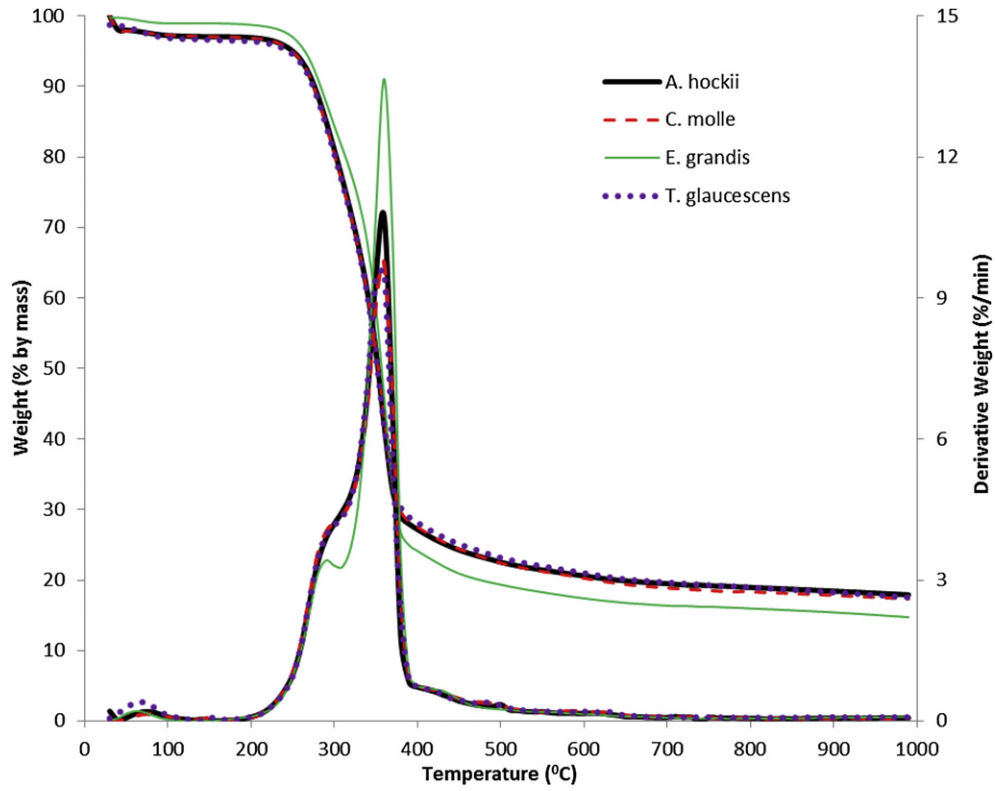


Fig. 1 – TGA curves for pyrolysis of the specified wood species plotted as mass percent and derivative weight as functions of temperature.

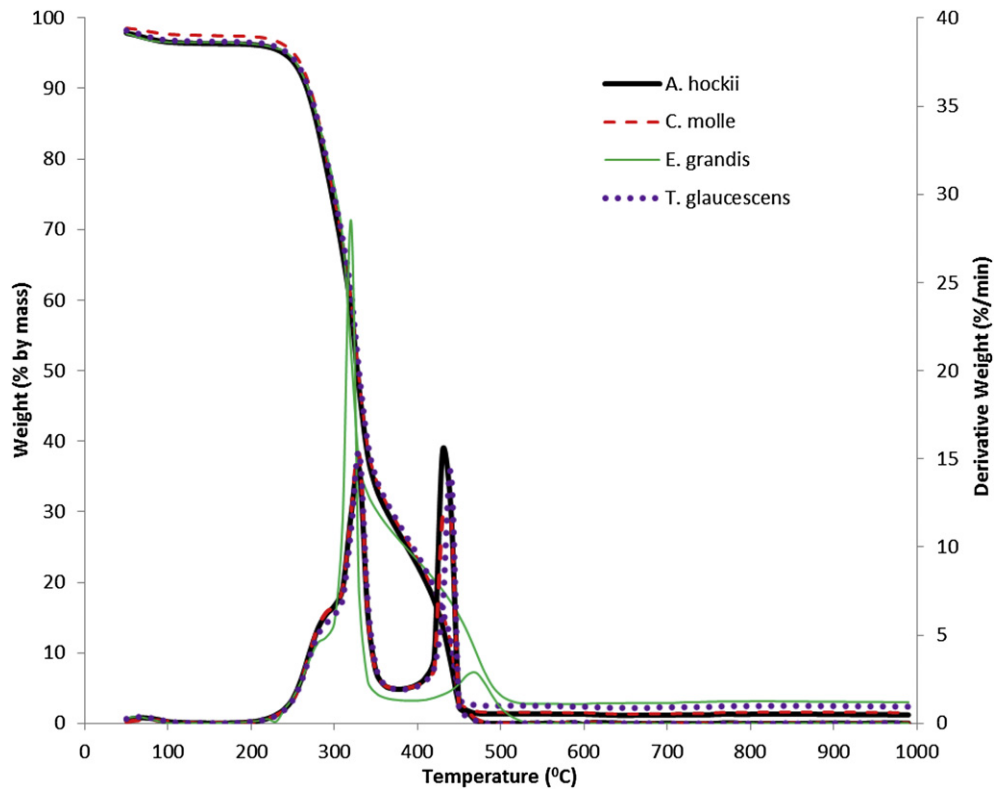


Fig. 2 – TGA curves for combustion of the specified wood species plotted as mass percent and derivative weight as functions of temperature.

4. Conclusion

The analytical data developed for the 4 examined species *E. grandis*, *T. glaucescens*, *A. hockii* and *C. molle* shows that sun dried wood from these is very suitable for thermochemical conversion including combustion and gasification on account of their high volatile content and their low ash mass. The ash qualities are quite benign with little tendency for ash-fusion under the conditions of combustion and gasification.

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