Biomass utilization for energy purposes in Kenya

Fuel characteristics and thermochemical properties

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Abstract

About forty percent of the world´s population, mostly inhabitants of countries with developing economies, rely on the traditional usage of biomass for energy purposes. The major negative consequences are environmental and health effects. Additionally, the most remarkable social consequence is rural poverty which is directly linked to lack of access to electricity. This places the questions related to biomass utilization for energy production at the core of global welfare. The present work was performed as a part of a larger research project funded by Formas and which involves Swedish and Kenyan partners. The aim of this study was to gather basic knowledge about the characteristics of relevant biomass from sub-Saharan Africa, more specifically from Kenya. Eight different types of biomass, including agroforestry trees, agricultural residues and water hyacinth, were evaluated according to fuel characteristics and thermochemical properties. Ultimate and proximate analyses of the collected biomass were carried out, in addition to heating values analyses. Moreover, the biomass was pelletized and a thermogravimetric analysis was performed in a single pellet reactor. Finally, the composition of the residual ashes was determined. The results show that there was a large variation in the fuel characteristics and thermochemical behaviour of the studied agricultural residues and water hyacinth biomass types, whereas agroforestry trees had rather similar properties and thermochemical behaviour when combusted at the same temperature. In addition, results from the ash composition analyses showed large differences among the studied biomass types, which can be used to better predict and solve problems related to the combustion of these biomass types.

Keywords: Bioenergy, Countries with developing economies, Wood, Agricultural residues, Thermochemical behaviour.

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1. Introduction

About 3 billion people, mostly living in countries with developing economies, rely on the traditional use of biomass for energy purposes, mainly cooking and heating (1). This is especially the case in sub-Saharan Africa, where 80% of the population relies on the traditional usage of biomass (1). Moreover, about 1200 million people living in countries with developing economies lack access to electricity (2). In addition to that, electricity cuts are currently one of the biggest concerns among owners of medium and large scale industries in countries with developing economies. To avoid the dependence on unreliable grids, auto production of energy and decentralized energy production are of key importance (3).

The use of biomass for energy production is at the core of the global welfare discussion. This is due to a number of reasons; First, the lack of access to energy is considered to be directly related to rural poverty (3),(4). Second, in countries with developing economies, indoor air pollution derived from the use of solid fuels for heating and cooking is one of the main causes of respiratory infections and respiratory-related deaths (5),(6). Third, forest degradation and deforestation have multiple negative impacts, for instance, soil fertility decline (7) and increased carbon emissions.

Compared to biomass utilization for energy production, other renewable energy alternatives, for instance, solar or wind energy, have recently experienced a high technological development. While the use of solar panels and wind turbines of small and medium scale is gaining presence in countries with developing economies, the available knowledge and experience on biomass utilization have not yet been implemented in these countries. Since the traditional use of biomass is present in the everyday life of millions of people in countries with developing economies, and will most likely be in the next coming decades, there is an urgent need to transfer the knowledge on biomass utilization for energy production to these countries in order to achieve a more sustainable, efficient and safe use of biomass.

There are two biomass types which are especially attractive for energy production in sub-Saharan Africa, namely agricultural residues and agroforestry trees from improved fallows. Both these biomass types are interesting because they do not compete with food production over land, as it is the case of agricultural crops grown to produce fuel (fuel vs. food competition). Improved fallows (8) is an agroforestry technique in which crop and tree plantations are alternated in time, and this technique is proven to have positive effects on soil restoration. Crop yields increments of 50-100% have been measured following improved fallows (9–12). The bottleneck of improved fallows is that the farmers cannot grow food crops during the fallow period in which the trees are growing. That is, there is a gap in the food

production cycle and therefore an economically founded argument against the implementation of improved fallows. In the case of sub-Saharan countries bordering Lake Victoria, an additional type of biomass worth considering is water hyacinth. In recent years, water hyacinth has become a major invasive plant in Lake Victoria, mainly due to eutrophication linked to a high sediment content. This, in turn, has negative ecological impacts, as for instance on fish, and therefore the removal and utilization of these plants is highly relevant to alleviate the problem.

In the present study, different fuel- and combustion related analyses were performed to determine the characteristics of the different biomasses from a thermochemical utilization perspective. The specific objectives of this study were to; I) Determine fuel characteristics and properties of different biomass types collected in Kenya, and II) Evaluate the thermochemical conversion behaviour of the collected biomass types.

2. Material and methods

2.1 Biomass collection

Biomass samples were collected during a field campaign carried out in Kenya in April 2016 (Fig. 1). A total of 8 biomass types, namely sugarcane bagasse (BG), coffee husk (CH), rice husk (RH), sunflower cake (SF), water hyacinth (WH), *Casuarina* sp. (CAS), *Grevillea* sp. (GRE) and *Sesbania sesban* (SES), were collected and shipped to Sweden for further fuel preparation and analysis.

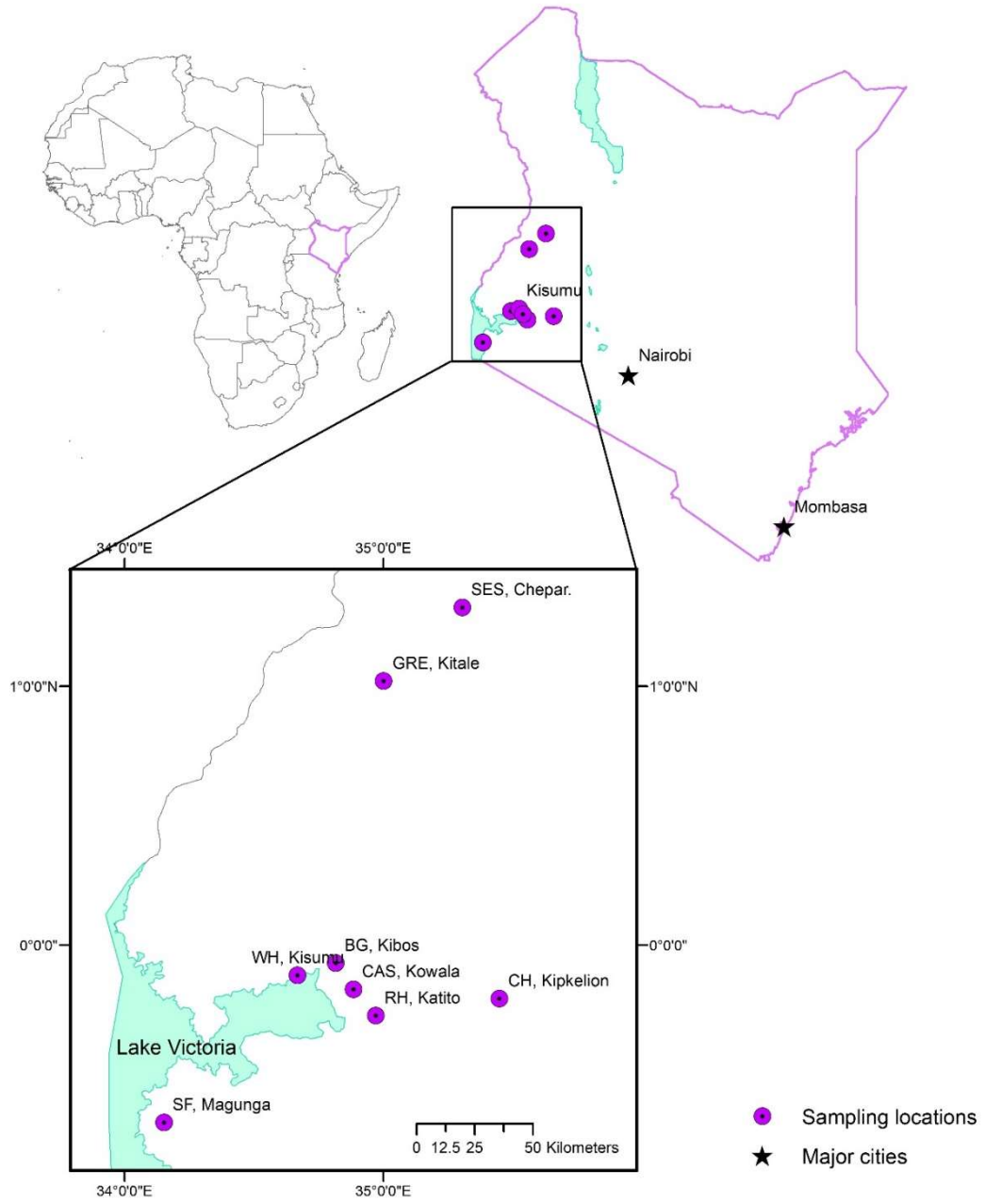

Figure 1. Location of the places where biomass samples were collected.

Sugarcane bagasse (BG) was collected at Kibos sugar factory, coffee husk (CH) was collected at Kipkelion coffee mill, rice husk (RH) was collected at Katito rice mill, sunflower cake (SF) was collected at Magunga, and water hyacinth (WH) was collected in the Kisumu bay of Lake Victoria. *Casuarina* sp. (CAS) was collected in the village of Kowala, *Grevillea* sp. (GRE) was collected in Kitale and *Sesbania sesban* (SES) was collected in Cheperaria (Fig.1 and 2).

Biomass samples were classified into two groups. The first group is composed of agricultural residues and water hyacinth and includes 5 biomass types, i.e. sugarcane bagasse (BG), coffee husk (CH), rice husk (RH), sunflower cake (SF) and lastly water hyacinth (WH). The second group is composed of 3 agroforestry tree species, i.e. *Casuarina* sp. (CAS), *Grevillea* sp. (GRE) and *Sesbania sesban* (SES). In the case of Sesbania, a further separate analysis of the bark (SES_{BK}) and the stem wood (SES_{ST}) were carried based on the knowledge that Sesbania branches are often given to livestock, which then eats the bark, and afterwards the branches without bark are used for cooking purposes.

Figure 2. Biomass collection. From top left to top right; bagasse, coffee- and rice husk and sunflower cake collection. From bottom left to bottom right; water hyacinth, Casuarina, Grevillia and Sesbania collection.

2.2 Pellets preparation and analysis of physical properties

The biomass samples were ground to a fine fraction (<4 mm) and dried to a moisture content of approximately 10 %. Afterwards, pellets with a diameter of 8 mm were made using a semi-industrial scale pelletizer provided with a ring die (PP150 Compact) manufactured by Sweden Power Chippers and similar to the one used by Larsson *et al*. (13) (Fig. 3). Sunflower cake could not be pelletized in the semi-industrial pelletizer due to its high oil content; And because of this problem, sunflower cake was pelletized with a laboratory scale pelletizer.

Figure 3. Pelletized biomass. a) Detail of the ring die. b) From top left to top right; bagasse, coffee husk, rice husk, sunflower cake and water hyacinth pellets and from bottom left to bottom right; Casuarina, Grevillea and Sesbania pellets.

To gain a better understanding of the characteristics of the pellets made from the studied biomass types, pellet durability and specific density of the used pellets were measured.

Mechanical durability was determined in a pellet tester (Q-tester) manufactured by Simon Heesen BV (13). For each biomass type, two samples of 500 grams were tumbled during 500 revolutions. The biomass samples were passed through a sieve with a 3.15 mm mesh. Afterwards, the fraction that remained on the sieve was weighed. The percentage of the remaining sample was used as the mechanical durability index.

Furthermore, the specific density of the pellets was calculated by dividing the mass of the pellet by its volume, estimated through measurements of its length and weight. Due to the fact that the pellets were rectified to achieve the desired weight, the edges were rather perpendicular to the sides of the pellets and therefore the obtained length measurements for the calculation of the specific density were considered to be acceptable for this study.

2.3 Standard fuel analysis

The standard fuel analyses were carried out by Bränsle Laboratoriet AB. The analyses included the calculation of lower and higher heating values, proximate and ultimate analyses and determination of the ash content. The applied standards for the carried analysis are compiled in table A1 in appendix 1.

2.3.1 Heating values

Lower and higher heating values were measured for the 10 studied biomass types and treatments. In contrast to the higher heating value, the lower heating value does not take into account the heat of vaporization of the water contained in the sample (14). Moreover, in this report, only lower heating values on total weight basis and on ash free basis are presented.

Additionally, all heating values obtained from the analyses are compiled in Table A2 in Appendix 1.

2.3.2 Proximate analysis

The proximate analysis included the measurement of the volatile and the ash fractions of each biomass type. The content of fixed carbon was then calculated by subtracting the obtained volatile matter and ash weights from the total weight of the sample. Ash content was determined at 550°C. The results from the proximate analysis are presented in percentage of weight and calculated on dry weight basis.

2.3.3 Ultimate analysis

The ultimate analysis included measurements of the contents of the following main fuel constituents: carbon (C), oxygen (O), hydrogen (H), nitrogen (N), chlorine (Cl) and sulphur (S). The values are expressed on the percentage of weight on dry basis. Due to the high ash content of some of the biomass types studied, the ash content is also presented with the ultimate analysis to illustrate the importance of the ash content when understanding the results from the ultimate analysis.

2.4 Ash composition

In order to determine the ash composition, the samples were pre-ashed and analyzed using a Scanning Electron Microscope (SEM) equipped with an Energy Dispersive X-ray Spectroscopy (EDS) detector. All the parameters, with the exception of temperature, that the Swedish standard SS 1B 71 71 (Biofuels-Determination of ash content) describes to determine the ash content of biomass were applied. The temperature was set to 500°C instead of 550°C as the standard establishes, based on the fact that the ashing process takes places in an oxidative atmosphere and that the temperatures risked exceeding the melting points of rather volatile elements (e.g. chlorine and sulphur in combination with alkali metals).

The elemental composition of the ashed samples was determined by using a SEM XL 30 ESEM, manufactured by Phillips, and an Edax EDS detector, in accordance with previous studies (15), (16). Due to a technical failure on the EDS sensor during the campaign, elemental ash composition could only be determined for 5 of the prepared biomass assortments, i.e. the agricultural residues and the water hyacinth pellets biomass types. The results of the ash composition analysis are presented in mole fraction basis.

2.5 Thermogravimetric analysis and combustion process

A well-established method for research and development regarding biomass combustion is the application of macro thermogravimetric analysis (macro-TGA). Time and mass loss are recorded as a single pellet is converted and combusted in a thermogravimetric setup. Among the parameters that can be varied, there are process temperature, atmosphere, and flow of the supplied air.

The combustion process, or more correctly the full conversion, is the comprehended time between the point at which a sample starts to lose weight and the point at which the weight loss stops, that is when the weight of the sample is constant independently of the time that the sample stays in the furnace. However, this conversion process is composed of two rather distinct phases, i.e. the fuel devolatilization phase and the char combustion phase (Fig. 4).

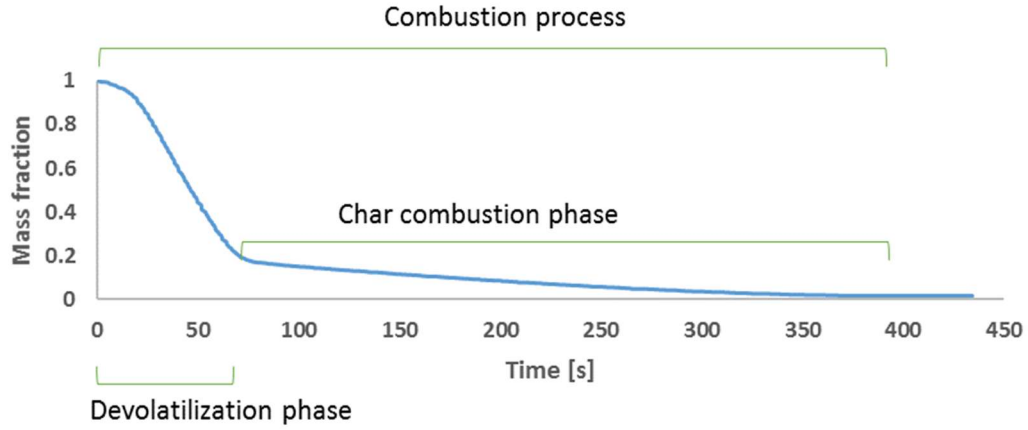

Figure 4. Illustration of a typical plot made with data obtained from an M-TGA experiment in which the combustion process, the devolatilization and the char combustion phases are marked.

In this study, the duration of the devolatilization phase, and therefore the start of the char combustion phase, has been calculated by analysis of the obtained data. For each temperature and group of biomass types, two time points were chosen to create a trend line over the devolatilization phase and two times to create a trend line over the char combustion phase (Fig. 5). The times at which the curve described by the collected values over the combustion process branched from the respective trend lines were collected.

Furthermore, for each combusted sample, an average value of the two times at which the collected data differed from the described by the trend lines was calculated and set as the time at which the devolatilization phase ended. Moreover, the time of the char combustion phase was calculated by subtracting the devolatilization time from the total combustion process time.

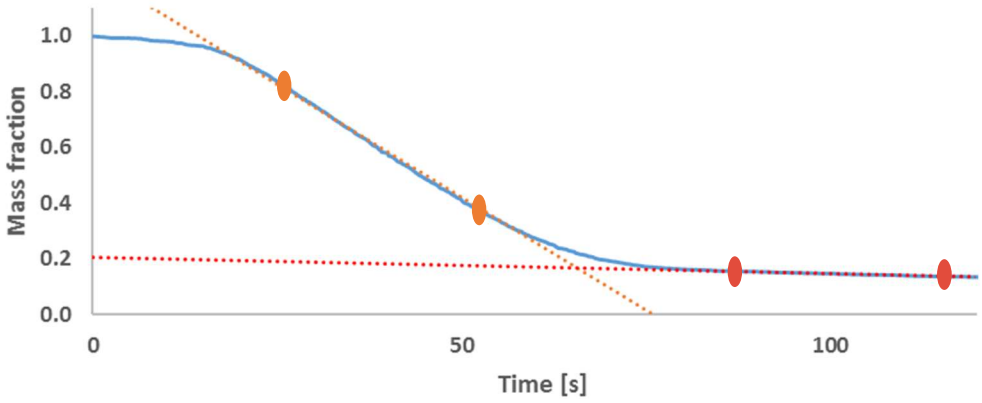

Figure 5. Chosen time points and the corresponding trend lines over the devolatilization and the char combustion phases.

The two time points used to create the trend lines for each temperature, phase, and biomass type group are compiled in table 1.

Table 1.Times points used for the created trend lines in the data analysis.

	Time points [s]			
	Devolatilization phase		Char combustion phase	
	700°C	**950°C**	**700°C**	**950°C**
Agricultural residues and WH	10 85	10 25	100 185	66 98
Agroforestry trees	18 68	10 43	85 147	66 98

2.5.1 Macro-TGA setup and experimental settings

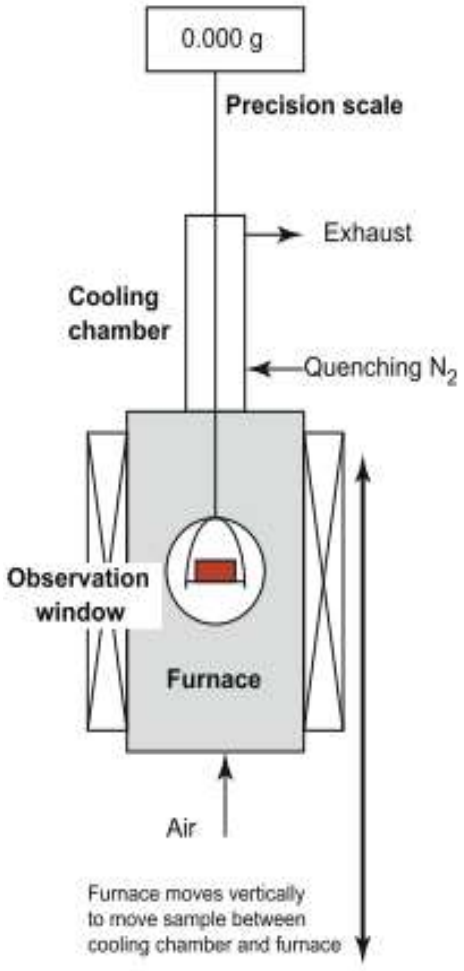

Figure 6. Schematic illustration of the M-TGA setup used on this study. Reprinted from Biswas et al. (15).

Combustion of single pellets was carried out at a customized macro-TGA furnace with dimensions 200*130*130 mm (16). The single pellet reactor is composed of a combustion chamber and a cooling tower. Moreover, an analytical balance is located above the furnace from which the pellet is suspended in a basket. The furnace is assisted by a pneumatic cylinder, located underneath, that moves the furnace up and down (Fig. 6). In this study, a platinum basket (Pt-basket), on which the pellet was placed, was used as it was observed at previous lab trials that certain basket materials are affected by temperature. The weight of the pellet was automatically registered with a frequency of 7 times per second until the end of the combustion phase.

The heating system of the furnace consists of resistances mounted on the walls (Fig. 7). The furnace temperature is measured by a thermocouple located at approximately two centimetres from the sample and controlled by a Proportional Integral Derivate (PID) controller.

Combustion air is supplied to the combustion chamber. In this study, atmospheric air (i.e. a mixture of ca. 21 % O_2 and 79 % N_2) was used and supplied at a rate of 15 litres per minute. The combustion air passes through a tubing loop located at the bottom of the furnace in which the air is pre-heated.

Two combustion temperatures were used in this study, 700 and 950°C. Furthermore, the pellets were rectified to have straight edges and a weight of 1 gram with a tolerance of ± 0.0005 grams.

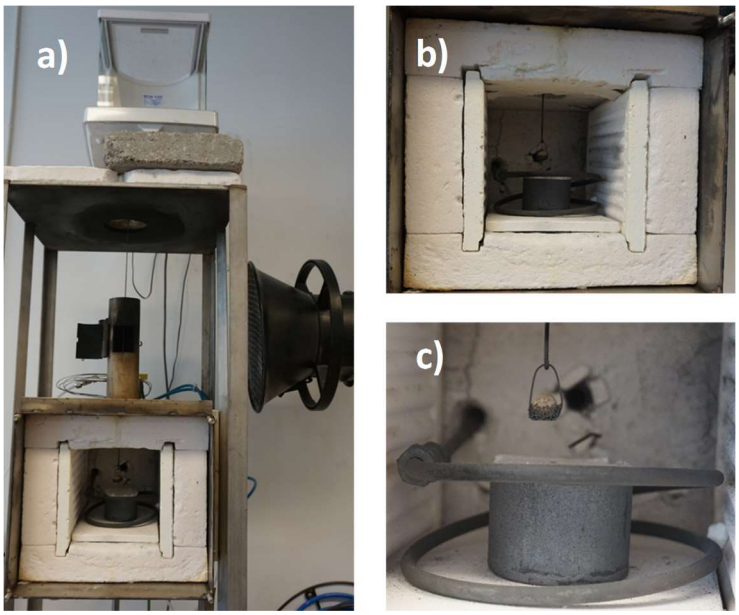

Figure 7. a) M-TGA setup at the TEC-Lab facilities at Umeå University. b) The interior part of the m-TGA furnace with the heaters located on the walls. c) detail of the thermocouple, the air preheating loop and the basket with a pellet in the furnace.

2.6 Chemical analysis of the residual ashes

The samples that had undergone the combustion process at the macro-TGA, were further analysed to determine their elemental composition with an SEM-EDS instrumental setup (described in section 2.4).

In order to avoid perturbations on the analyses caused by big particles, the collected ash samples were previously smashed.

3.Results

3.1 Specific density and pellets durability

The specific density and the pellets durability were tested for the pellets pelletized with the semi-industrial pelletizer, namely all studied biomass types but sunflower cake.

Table 1. Average values (±SD) of the specific densities of the 4 studied agricultural residues and the 3 studied agroforestry trees biomass types.

Agricultural residues and WH

Biomass type	***n***	***Specific density [kg/m^3]***
Bagasse	6	1341 ± 15
Coffee husk	6	1299 ± 19
Rice husk	6	1400 ± 61
Water hyacinth	6	1465 ± 35

Agroforestry trees

Biomass type	***n***	***Specific density [kg/m^3]***
Casuarina sp.	6	1261 ± 38
Grevillea sp.	6	1270 ± 55
Sesbania Sesban	6	1311 ± 11

The specific density of the used pelletized fuels for the macro-TGA analysis are compiled in Table 2. The specific density of the studied pellets ranged between around 1261 and 1465 kg/m^3. More precisely, water hyacinth pellets were the ones with the highest density among the agricultural waste and WH group, and Sesbania Sesban the ones with the highest specific density among the pellets made of biomass from agroforestry trees. Pellets made of coffee husk and Casuarina were measured to have the lowest specific density among the studied biomass types. Pellets made of rice husk were measured to be the ones with the highest variation in weight among the 6 measured repetitions. Lastly, the variation in weight among Sesbania Sesban pellets was measured to be the lowest.

The mechanical durability of the pelletized fuels used for the macro-TGA analysis is shown in Table 3.

Table 2. Mechanical durability [%] of the 4 agricultural residues and the 3 agroforestry trees biomass types pelletized for this study.

Agricultural residues and WH		
	n	***Mechanical durability [%]***
Bagasse	2	97 ± 0.1
Coffee husk	2	81 ± 1
Rice husk	2	88 ± 0.1
Water hyacinth	2	98 ± 0.2
Agroforestry trees		
	n	***Mechanical durability [%]***
Casuarina sp.	2	89 ± 3
Grevillea sp.	2	89 ± 0.2
Sesbania Sesban	2	98 ± 0.2

Mechanical durability ranged between around 81 and 98% among the tested pellets. Water hyacinth pellets were measured to be the ones with the highest mechanical durability and coffee husk pellets turned to be the ones with the lowest mechanical durability. The variation in mechanical durability of the pellets made of Casuarina was measured to be the highest among the seven tested biomass types. The mechanical durability of both bagasse and rice husk pellets was measured to have the lowest variation among the studied pellets.

3.2 Heating values

Figure 8 shows a compilation of the lower heating values expressed on total weight and on ash free basis of the analysed biomass types, namely 8 biomass types plus 2 treatments.

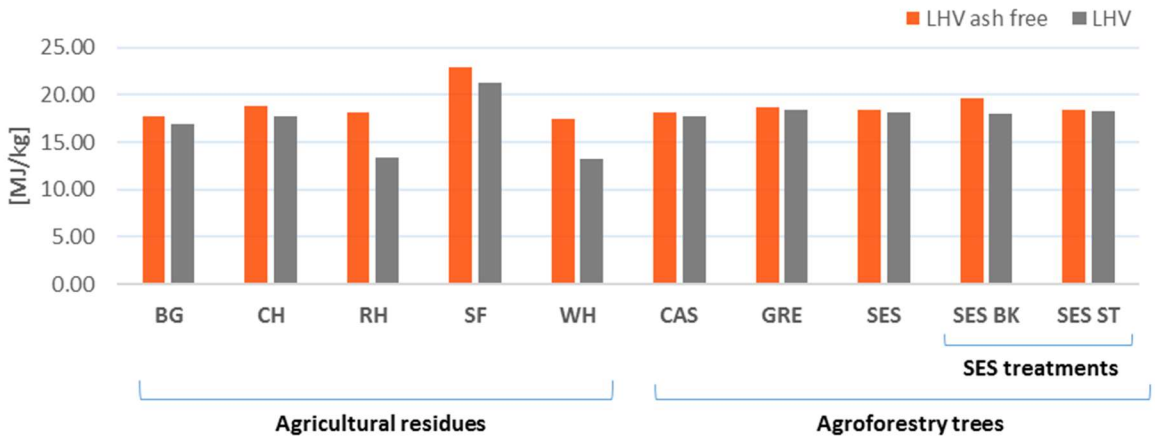

Figure 8. Higher and lower heating values of the five agricultural residues and WH biomass types (sunflower cake, coffee husk, bagasse, rice husk and water hyacinth).

Lower heating values ranged between around 23 and 13 MJ/kg. Sunflower cake turned to be the biomass type with the highest heating values expressed both on ash free and on a total weight basis. Water hyacinth was the biomass type with the lowest heating values both expressed on ash free and on a total weight basis.

3.3 Proximate analysis

Figure 9 shows fractional values (weight basis) of ash content, fix carbon and volatile matter for the 8 studied biomass types and the 2 treatments (SES_{BK} and SES_{ST}). Values obtained from the proximate analysis are compiled in Table A4 in appendix 1.

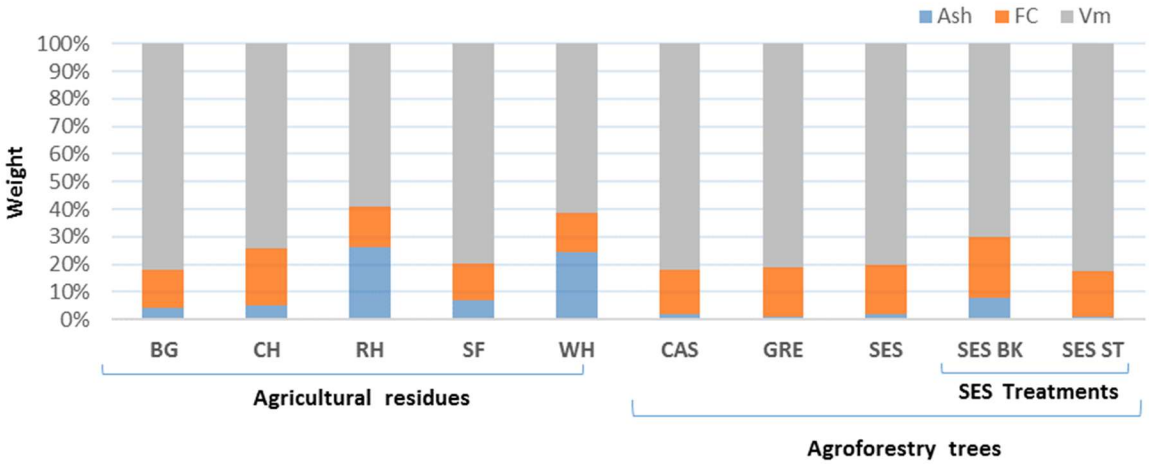

Figure 9. Ash content (Ash), fix carbon (FC) and volatile fraction (Vm) of the agricultural residues and WH and agroforestry trees biomass types expressed on a dry basis and weight percentage.

Ash content ranged between 1 and 26%. Rice husk and water hyacinth are the biomass types with the highest ash content, namely around 25%. The ash content among the agroforestry trees ranged between 1 and 2%.

The content of fix carbon ranged between 22 and 13%. Sesbania bark is the biomass type with the highest fix carbon content followed by the coffee husk. The biomass type with the lowest fix carbon content among the studied was sunflower cake with around 13%.
The fraction of volatile matter ranged between around 82 and 59%. Sesbania stem was the biomass type with the highest fraction of volatile matter and rice husk was the type with the lowest content of volatile matter.

3.4 Ultimate analysis

The presented values regarding the ultimate analysis are presented in weight percentage. Ash content values are presented by side ultimate results in order to give a better perspective of the composition of the studied fuels (Fig. 10). Carbon, oxygen, and nitrogen are the predominant elements in the 10 studied biomass types and treatments given that are structural elements. The values of the ultimate analysis are compiled in Table A4 in Appendix 1.

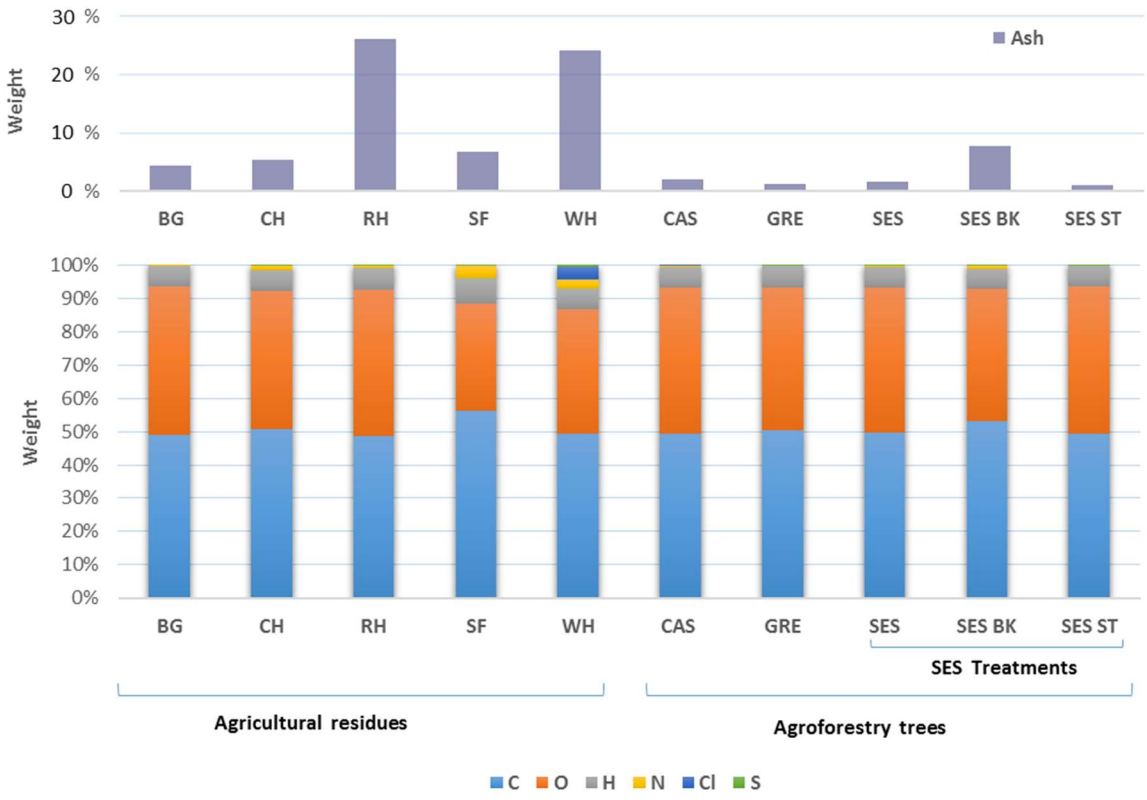

Figure 10. Ultimate analysis of the agricultural residues and WH and agroforestry trees biomass types expressed in weight percentage.

Carbon content ranged between around 52 and 36%. Sunflower cake was the biomass type with the highest carbon content and rice husk with the biomass type with the lowest carbon content.

Sesbania stem and Casuarina were the biomass types with the highest and rather similar oxygen, namely 43%. Water hyacinth was the biomass type with the lowest oxygen content, more precisely 28%.

Hydrogen content ranged between around 7 and 5%. Namely, sunflower cake was the biomass type with the highest hydrogen content, the biomass types with the lowest hydrogen content were water hyacinth and rice husk.

Sunflower cake was the biomass type the highest nitrogen content, namely 3.5%. Bagasse and Sesbania stem were the biomass types with the lowest nitrogen content, namely around 0.2%.

Chlorine content ranged between 0.02 and 0.09% for all the studied biomass types but water hyacinth. Chlorine content for water hyacinth was 2.9%.

The sulphur content ranged between 0.29 and 0.02. Water hyacinth was the biomass type with the highest sulphur content and bagasse the biomass type with the lowest.

3.5 C/H/O relation

Based on the ultimate analysis, one can assess the relation between carbon, hydrogen, and oxygen. An extensively used diagram for the comparison among different types of coal and traditional biomass is the so-called Van Krevelen diagram. In this diagram, the hydrogen to carbon relation is plotted against the oxygen to carbon relation. Certain areas, as for instance biomass or peat, are marked in the diagram. In this study, this diagram has been used to compare the 8 studied biomass types with the marked areas in the original diagram.

Among the studied agricultural waste and WH and agroforestry trees biomass types, sunflower cake turned to have the highest hydrogen to carbon ratio and the lowest oxygen to carbon ratio. Specifically, sunflower cake is pointed out of the area in which any biomass type should be according to the areas marked in the original diagram. As the arrow in Fig. 11 indicates, the higher the hydrogen to carbon ratios are and the lower the oxygen to carbon ratios, the higher the heating value will be, i.e. sunflower cake is the biomass type with the highest heating value. Furthermore, the location of all agroforestry trees biomass types barely varies among this group.

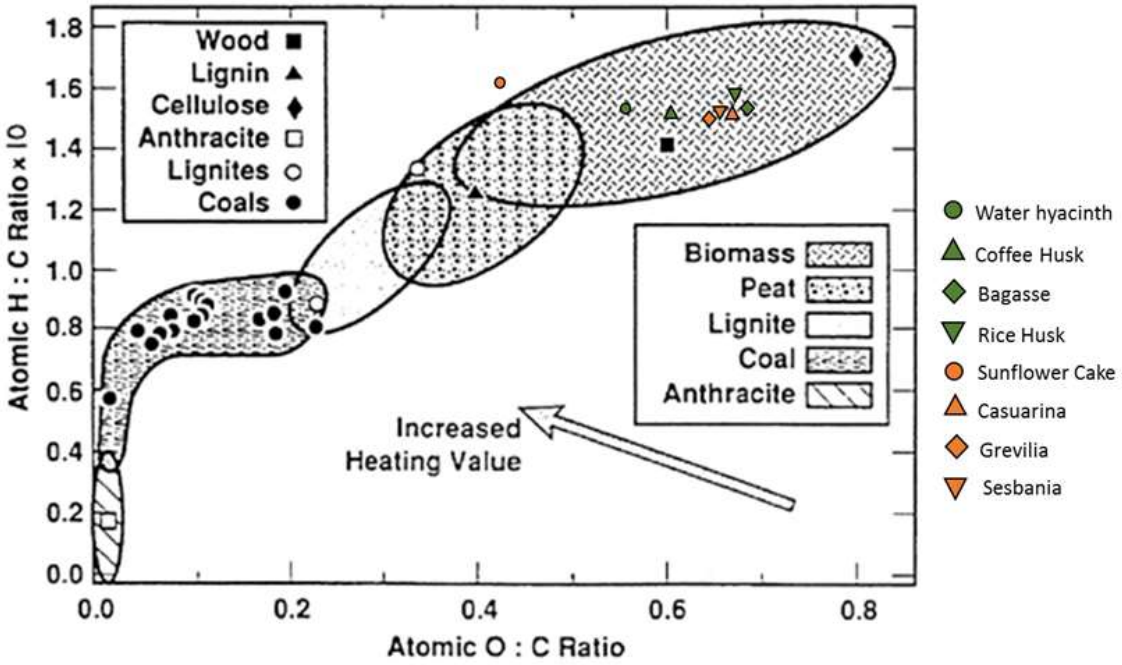

Figure 11. Van Krevelen diagram. The studied agricultural residues and WH biomass types are pointed on the Van Krevelen diagram. Modified from (17).

3.6 Chemical ash composition

As described in section 2.4, the analysis of the elemental composition of the ashes was carried on samples ashed at 500˚C and for the 5 agricultural residues and water hyacinth biomass types. As previously mentioned and due to a technical failure, only 5 biomass types could be analysed. The here presented values are expressed in mole fraction and compiled in Table A6 in Appendix 1.

In general, silicon and potassium are the most abundant elements in the ash of the five studied biomass types, while sodium and sulphur are the scarcest elements (Fig. 12).

The biomass type with the highest amount of potassium was coffee husk followed by sunflower cake. Rice husk has the lowest amount of potassium in its composition.

Water hyacinth was the biomass with the highest amount of sodium in its composition. The proportion of calcium content is highest for coffee husk, followed by water hyacinth and sunflower cake. The proportion of magnesium is highest for sunflower cake. Bagasse is the biomass type with the highest amount of aluminium and iron on its ash.

The ash from rice husk is the one with the highest amount of silicon, accounting for 86% of its composition, followed by bagasse which has around 57%.

The proportion of phosphorus and sulphur in the ash is highest for sunflower cake.

Water hyacinth ash stands out for its large amount of chlorine, accounting for around 22 % of its composition, compared to that for the other four studied biomass types, which is always lower than 1.5 %.

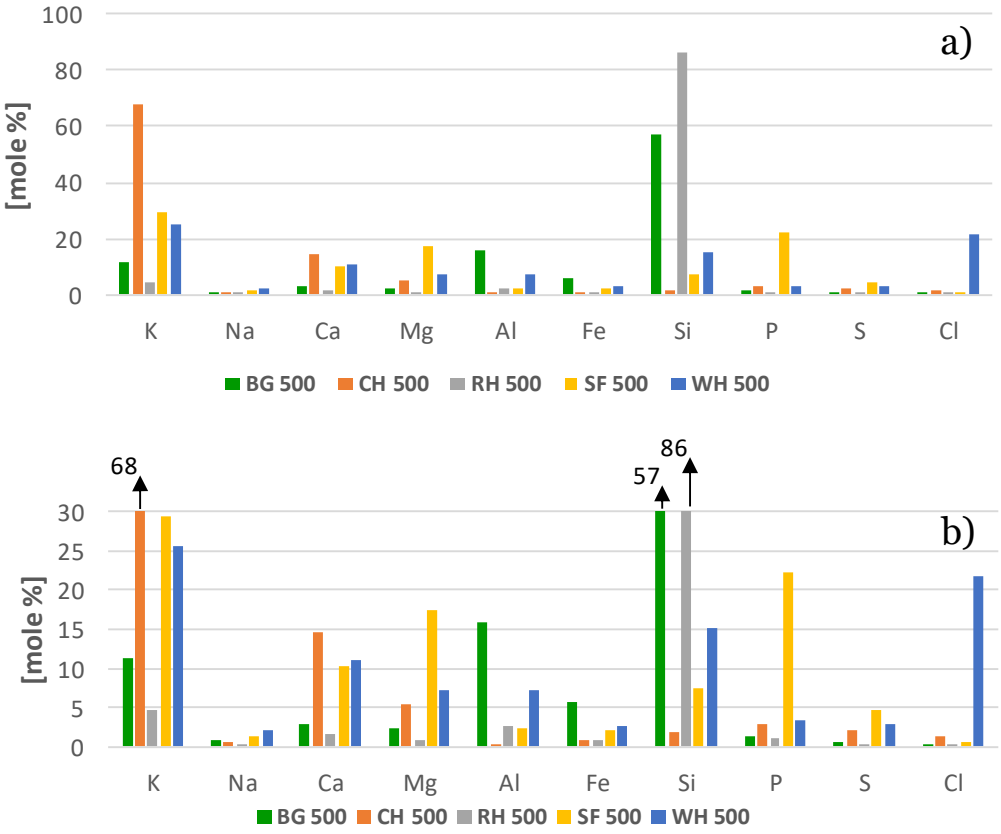

Figure 12. Ash composition (in moles %) of the studied agricultural residues and WH biomass types. a) The molar proportion of potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), aluminium (Al), iron (Fe), silica (Si), phosphorus (P), sulphur (S) and chlorine (Cl). b); Enlargement of elements contained in a lower content than 25% of the Figure 3a).

3.7 Thermal conversion

The 8 biomass types have different mass loss rates when combusted at 700°C and 950°C (Fig.13). Average values of three combusted pellets per each biomass type are compiled in tables A6 to A9 in Appendix 1.

As shown in Figure 13, more than 20% of the original weight of water hyacinth and rice husk remained left after the combustion process was completed at 700°C (top left). The other 3 biomass types that belong to this group had a rather similar mass loss, namely around 95% of its original weight was converted. The combustion process and the devolatilization and char combustion phases were considerably shorter when agricultural waste and WH were combusted at 950°C (bottom left). As in the case of combustion carried at 700°C, a considerable fraction of the rice husk pellets remained left after the combustion process was completed, pellets made of water hyacinth turned to have a higher mass loss when combusted at 950°C.

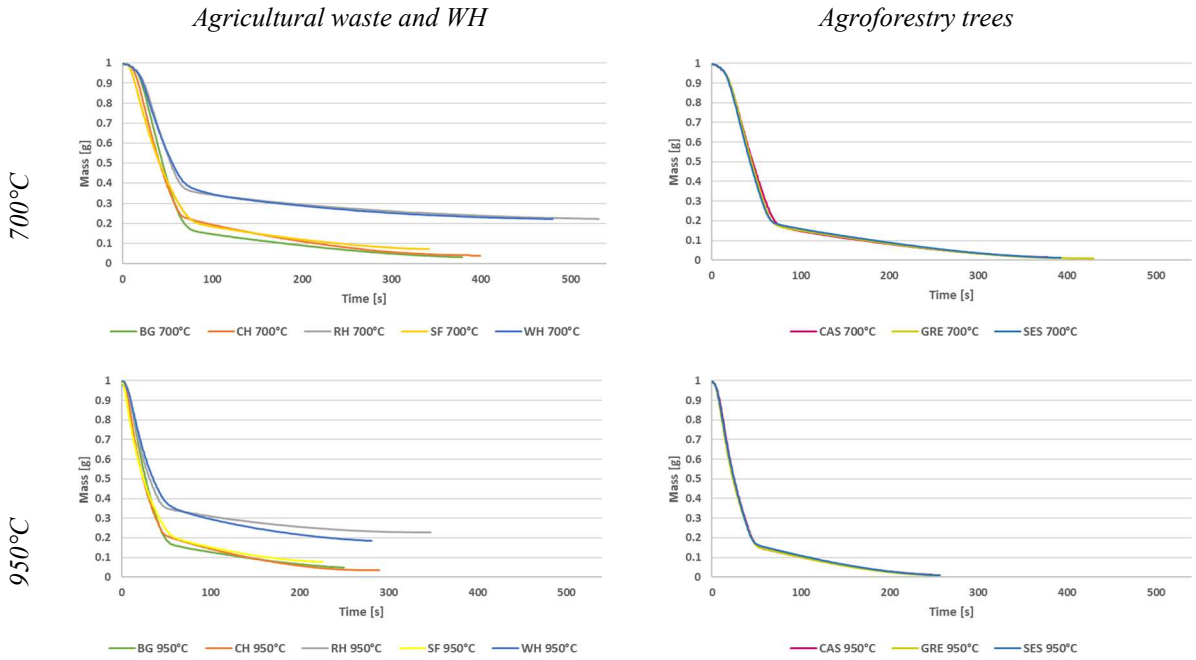

Figure 13. Mass loss rate diagram of the average values (±SD, n=3) for the 8 studied biomass types combusted at 700 and 950°C.

In contrast to the notable variation among the agricultural waste and WH pellets, pellets made of agroforestry trees had a rather similar behaviour over the combustion process regardless the combustion temperature.

As observed in the dataset obtained by the combustion of agricultural waste and WH, it took the considerably shorter time to complete both the combustion process and the devolatilization and the char combustion phases when the combustion was carried at 950°C (bottom right) instead for 700°C (top right).

As described in section 2.5, the duration of the devolatilization and the char combustion phases was calculated by analyses of the obtained data from the macro thermogravimetric analysis. Lastly, the duration of the char combustion phase is calculated. The obtained times are compiled in table 4. Additionally, tables A6 to A9 in Appendix 1 compile the obtained values from the analysis of the data obtained from the thermogravimetric analysis.

Table 4. Times for the combustion process, the devolatilization phase and the char combustion phase for the 8 studied biomass types combusted at 2 temperatures.

			Devolatilization [s]	Char combustion phase [s]	Combustion process [s]
Agricultural residues and WH	Bagasse	700°C	69	333	402
		950°C	43	206	249
	Coffee husk	700°C	61	329	390
		950°C	37	264	300
	Rice husk	700°C	65	525	590
		950°C	39	307	346
	Sunflower cake	700°C	74	266	340
		950°C	43	174	217
	Water hyacinth	700°C	70	416	486
		950°C	41	260	301
Agroforestry trees	Casuarina sp.	700°C	80	298	378
		950°C	47	201	248
	Grevillea sp.	700°C	75	355	430
		950°C	46	209	255
	Sesbania Sesban	700°C	73	320	393
		950°C	48	212	260

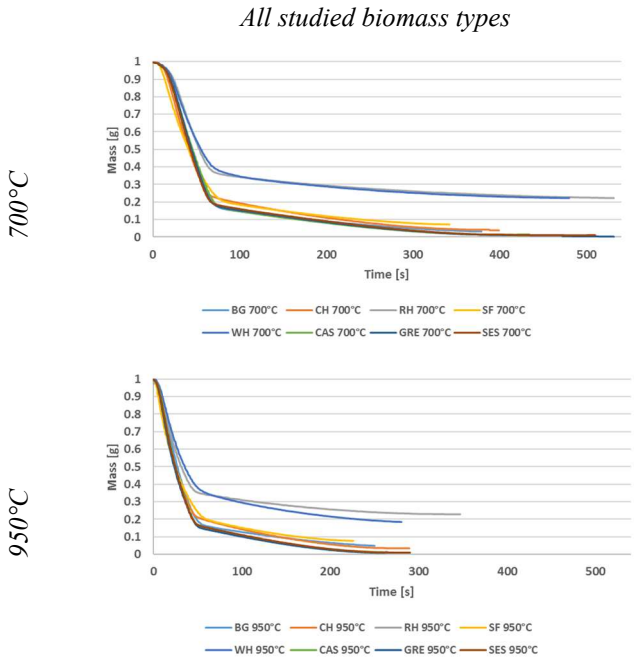

Figure 14. Mass loss rate diagram of the average values (±SD, n=3) for the 8 studied biomass types. Top; combusted at 700°C and left; 950°C.

Compiled combustion processes at both temperatures for the 5 agricultural residues and WH and the 3 agroforestry trees biomass types are shown in Figure 14. As previously shown in Figure 13, rice husk and water hyacinth pellets do not follow the same thermogravimetric pattern than the other pellets made of other biomass types. However, all other biomass types follow a similar pattern for each of the corresponding temperatures. In other words, the

combustion temperature and the ash content determine the thermogravimetric pattern rather the biomass type.

3.8 Ternary compositional diagrams

The residual ashes obtained after the thermogravimetric analyses were further analysed with the previously SEM-EDS setup. In order to gain a better understanding about how the ash composition changed over the combustion process, the chemical composition of the residual ashes obtained from the ashing (500°C) and the obtained from thermogravimetric analyses (700 and 950°C) were compared as follow.

The two constructed ternary diagrams (Fig.15), show that regardless the combustion temperature, coffee husk ash is characterized by the predominance of alkali metals (Na+K), while rice husk and bagasse ash is characterized by the predominance of silica. Water hyacinth ash, on the other hand, has a rather balanced composition, with the exception of an increase in the predominance of silica at 950˚C.

3.8.1 K+Na, Cl+S and Si+P diagram

The composition of rice husk and bagasse ash remains fairly constant despite the increment of the combustion temperature. The ash composition of coffee husk is rather similar under 500˚C and 700˚C, dominated by alkali metals, but it moves slightly away from the alkali corner of the triangle when the combustion process is carried at 950˚C.The composition of water hyacinth is located approximately at the centre of the triangle for 500˚C and 700˚C while it moves drastically towards the silica corner when the combustion process is carried at 950˚C.

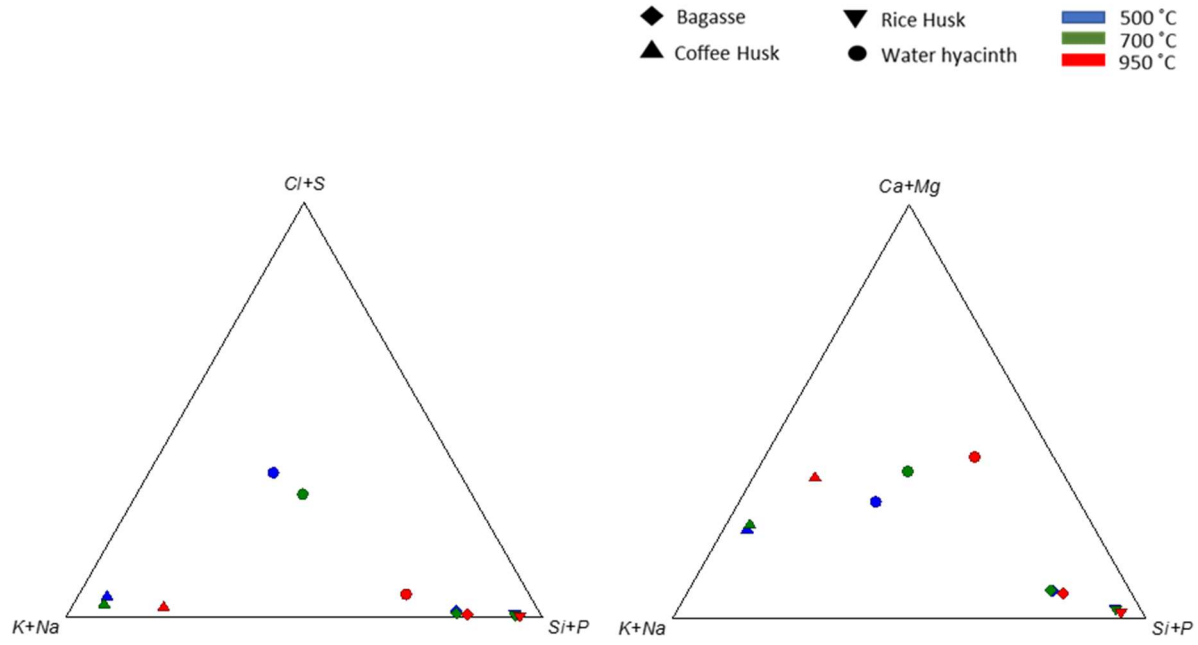

Figure 15. Ternary compositional diagrams for the 4 agricultural residues and WH biomass types with 3 tested temperatures. a) K+Na, Cl+S ans Si+P diagram. b) K+Na, Ca+Mg and S+Pi diagram.

3.8.2 K+Na, Ca+Mg and Si+P diagram

The ash composition of bagasse and rice husk remains fairly constant and dominated by silica independently of the combustion temperature.

The composition of coffee husk is dominated by the alkali metals when the sample is combusted at 500˚C and 700˚C, but it moves towards the upper corner (Ca+Mg) when the sample is combusted at 950˚C. In general, the ash composition of water hyacinth is rather balanced, but it moves slightly away from the alkali corner as the combustion temperature increases.

4. Discussion

4.1 Biomass selection and collection

The variation in the results, especially among agricultural residues and WH, regarding heating values, proximate and ultimate analysis and ash chemical composition gives proof that the aim of covering a wide spectrum of biomass with compositions was achieved. Furthermore, the two treatments carried on with *Sesbania sesban* showed promising/positive results regarding the usage of Sesbania as a suitable tree for energy production combined with agroforestry purposes and animal fodder.

There are various advantages and disadvantages regarding the use of either agricultural residues or agroforestry trees for energy production. In the case of combustion technologies that can use wood chips instead of pellets, agroforestry trees have the advantage that pelletization is not required, which might result in an energy and economic advantage.

On the other hand, agroforestry trees need to be grown for energy purposes while agricultural residues are a sub-product and crops are grown for food production. In the case of water hyacinth, its utilization for energy production would be highly beneficial, as it would lead to a decreased pressure on the lake and river ecosystems, which in turn would result in increased fish production and navigability, thereby positively affecting local livelihoods.

An indirect benefit of growing agroforestry trees as sources of biomass for energy production is the improvement of soil quality (10); If these trees are planted on fallow land (i.e. improved fallow) the farmers can obtain better harvests in the coming years. However, since land is left to fallow and crops are not grown during the fallow period, this represents a cost of opportunity in terms of food production. Thus, the implementation of improved fallows would ideally require a careful planning in order to optimize the benefits and not put food security at risk. A well-planned rotational planting method based on the alternation of crops and agroforestry trees for energy purposes could contribute to a better soil quality, increase crop yields and incomes, which would positively contribute to the livelihoods of people.

Biomass water content is a factor that needs to be considered as well when evaluating the suitability of the different biomass types for energy production. Water hyacinth sampled in this study contained more than 90% of water when harvested, which means that large amounts of work and energy are required to dry it. Another biomass type with a large content of water was bagasse, which contained around 50% of water when it was collected at the factory. Moreover, in the visited bagasse briquettes company, bagasse was dried in the sun; however, this cannot

be done during the rainy season, which constitutes a bottleneck for the drying process and also requires a large storage capacity.

4.2 Fuel and pellets properties

Among the studied biomass types, sunflower cake was the one with the highest heating values. However, sunflower cake is often used as animal fodder, which can make it a more expensive fuel compared to other residues. The heating values for the analysed agroforestry tree types were rather similar. Thus, from a heating value perspective alone, there was not any tree that stood out as being more suitable for energy production.

Among the ten studied biomass types and treatments, the ash content of rice husk and water hyacinth, namely around 25% in weight basis, is the most remarkable characteristic regarding the proximate analysis.

The available data on biomass composition for different biomass types is highly variable and also differs from the results of this study. According to Daya *et al.*, the ash content for bagasse varies between 1.8 and 22.1%, and the fixed carbon content varies between 7% and 14.95%. Ash content for coffee husk, are 2.4% and 2.8% according to Daya *et al.* (18) and Vassilev *et al.* (19), while results of this study indicate an ash content of 5.3% for coffee husk. Moreover, the ash content of rice husk is 18% and between 21.24 and 22.5% according to Vassilev *et al.* (19) and Daya *et al.* (18), while the results presented in section 2.3, show that the ash content for rice husk is 26.2%. In any case, and despite the representativity of the collected samples and the biomass characteristics linked to the area where the collected biomass types were grown, the values presented in this study have been obtained according to standard methodologies.

In the literature, the results of the ultimate analysis are usually presented in isolation. However, given the high ash content of some of the agricultural residues and WH biomass types analysed here, in this study, the results from the ultimate analysis are presented together with the ash content values.

Among the agroforestry trees, Sesbania is the only nitrogen-fixing species. Often, leaves and bark from Sesbania are used for animal fodder. In this study, it was investigated whether Sesbania biomass contained more N_2 than other tree species, and also whether there was a difference between the nitrogen contained in stem wood and bark. Analyses show that the stem only contains N_2 in parity with other tree species, whilst the bark contains 4-5 times as much N_2 as the stem wood, i.e. a large proportion of the N_2 contained in the tree is concentrated in the bark and small branches.

Being nitrogen content in the biomass the first indicator to look at when studying the emissions of NO_x, it is relevant to point out that sunflower cake was the biomass type with the highest nitrogen content (3.5%), followed by water hyacinth with 2.2%. Coffee husk has 1.2% of nitrogen on its composition while Sesbania bark accounts for 0.9%. The other studied biomass types included Sesbania stem, have less than 0.6% of nitrogen in its composition.

In concordance with the observed high oil content of sunflower cake when samples were collected, and its large heating value (the highest among the studied biomass types); Sunflower cake also has the highest hydrogen to carbon ratio and the lowest oxygen to carbon ratio (as illustrated in the Van Krevelen diagram presented in section 3.5).

Despite the large wood density variation among the studied agroforestry trees biomass types (20), the specific density of the pelletized biomass types ranged within a small span. In fact, even the specific density of the pellets made of agricultural residues and WH does not differ from the ones of pellets made of agroforestry trees biomasses.

The mechanical durability is related to the friction created on the die when the biomass is pressed through, that is why for instance sunflower cake could not be satisfactorily pelletized with the semi-industrial ring die pelletizer. Similarly, coffee husk caused a low friction and therefore its durability (69.9%) was lowest among the other biomass types. However, further experiments in which pellets might be combusted in larger amounts than in the here used macro-TGA setup might determine whether the pellets are resistance enough to be handled and combusted properly.

4.3 Detailed ash composition and thermochemical conversion properties

The high values of Al and Fe content found in the bagasse ash are likely caused by contamination from the industrial process in which the sugar is extracted from the sugar cane and bagasse is left as a by-product.

The results of the ash composition of bagasse were nearly constant regardless of the combustion temperature. That is, really low element release, if any, takes place when bagasse is combusted at temperatures up to 950°C. This would explain why one of the companies we visited in Kenya, that used bagasse briquettes, had big clinker problems on their boilers.

The predominant elements in the ash of coffee husk are cation forming elements (K, Ca, Mg). In contrast, the anion forming elements (P, Cl, S), are present at a much lower proportion than the cations. Thus, it would be interesting to perform complementary ash analysis, as for instance

an X-Ray Diffraction (XRD) analysis, in order to determine the specific crystalline structures of the coffee husk ash.

Coffee husk ash has a predominance of K on its composition, which remains constant between 500°C and 700°C; however, some element from the alkali corner (K+Na) seem to be released when the combustion is carried at 950°C. The observed evolution of the ash composition of coffee husk might be explained by the fact that the melting point of sodium chloride (NaCl) is 801°C. On the other hand, the content of Ca in the ash remains nearly constant when the combustion temperature is increased from 700°C to 950°C.

Rice husk ash has extremely high Si contents under the three studied combustion temperatures, 500°C, 700°C and 950°C. The fact that the composition does not vary when increasing the combustion temperature indicates that Si is not released, which can lead to problems of clinker formation. The melting point of silicon dioxide (SiO_2) is 1713°C.

As mentioned in the introduction section, the enhanced growth of water hyacinth in Lake Victoria is a consequence of eutrophication, and therefore high values of certain elements could appear when analysing this biomass type. Despite this has not been observed in this study, this aspect needs to be considered and analysed carefully in future research.

The ash composition of water hyacinth combusted at 700°C has a relatively small variation in comparison to the variation in the composition of the ashes obtained when the combustion was carried at 950°C. In any case, as it can be seen in Figure 10, K and Cl are released during the combustion process and more notably when the combustion process is carried at temperatures above 700°C. This can be explained by the fact that Potassium chloride (KCl) has a melting point of 770°C.

Regarding the thermochemical conversion, results from this study clearly demonstrate that the temperature at which the combustion process is carried out has a big impact on the thermochemical behaviour. Both the devolatilization and char combustion phases took place in a shorter time when the combustion temperature was higher. Moreover, except for rice husk and water hyacinth, which are the fuels with the highest ash content among the studied biomass types, all biomass types turned to have a similar thermochemical behaviour when combusted at 700 and 950°C respectively. Therefore the combustion temperatures at which combustion technologies of different scale, namely domestic, medium or industrial, operate should be taken into consideration. That might be of high relevance not only for designers, builders, and consumers but also for nongovernmental organizations or policy makers.

4.4 Method development

A platinum basket was used on the experimental macro-TGA setup, based on previous lab trials where it was observed that iron baskets were affected by temperature. However, there is still no consensus on what is the best material to build the macro-TGA baskets. For instance, Erlich *et al.* (21), used a stainless steel basket when studying the sugarcane bagasse pellets.

Usually, data obtained from the macro-TGA analysis is presented with normalized values ranging between 1 and 0 (15), (16). In this study, however, the data has not been normalized with the aim to show the amount of ash left in the basket once the combustion process has been completed. Furthermore and motivated by the fact that there are potential errors when data is normalized to 1, low weight tolerances have been used in this study compared to other studies (16).

Additionally, when analysing the release of different elements, it has to be taken into consideration that the temperature at which the furnace is set it is not equivalent to the temperature of the pellet over the whole process, as shown by Fagerström *et al.* (16).

4.5 Additional value of biomass utilization

The use of biomass for energy production has several advantages, for instance regarding carbon net emissions. In Kenya and other sub-Sharan countries where the grid is not stable and electricity cuts are common, the use of biomass for electricity production at small and medium scales could increase the autonomy of industries, companies, and households. Indeed, one of the main concerns among the owners of the visited industries was the problems derived from electricity cuts. Electricity cuts are common, especially during the rainy season, unpredictable and often last for several hours. These electricity cuts affect more severely middle and small scale industries which do not have emergency diesel generators and whose productivity can thereby be notably reduced.

4.6 Future research needs

Given the high environmental, health and social importance of biomass utilization in countries with developing economies, it would be of high relevance to adequately measure, investigate and report data on heating values, as well as ultimate and proximate analyses of different biomass types.

More comprehensive studies regarding biomass water content at the collecting point, biomass availability (quantity, temporal and spatial distribution) and cost of opportunity of biomass production or collection, would be a valuable knowledge contribution and a supporting

information to show public institutions and private actors what is the potential of different types of biomass to be used as energy source. Additionally, biomass production per area and time unit of agricultural wastes versus agroforestry trees would be an important aspect of studying in order to evaluate the suitability of each type of biomass.

Sunflower cake becomes attractive when looking at its heating value, but competition as a source of fodder and NO_x emissions are further aspects that should be studied.

An investigation on which basket materials are suitable to be used in the macro-TGA experiments would a valuable knowledge contribution.

An X-Ray Diffraction analysis of the ashes, from which its crystalline structure can be determined, would give a better understanding of the ash chemistry of the different fuels.

In the case of water hyacinth, it has been seen that KCl is released when it is combusted at temperatures higher than 700°C. Therefore, implications of KCl release are relevant to be studied in the context of water hyacinth utilization.

Further studies regarding N_2 content on different nitrogen fixing trees used in agroforestry systems would be of interest. Additionally, complementary studies as for instance on the multipurpose usage of trees i. e. as sources of animal fodder and fuel or studies related to NO_x emissions would be valuable as well.

5. Conclusions

Results from this study show that there was a large variation among most of the studied biomass types in terms of their characteristics, their properties as fuels and their thermochemical conversion behaviour. Most specifically, agricultural waste and WH biomass types differed both from agroforestry trees and also amongst them. In general, the thermochemical behaviour, as well as the biomass and pellets characteristics of the three analysed tree species, were rather similar.

Specifically, some of the most remarkable results of this study are:

- Sunflower cake was the biomass type with the highest heating value.
- Rice husk and water hyacinth had around 25% of ash in their composition.
- Most of the nitrogen contained in Sesbania, a tree used in agroforestry, was found to be in the bark.
- Rice husk and bagasse had a very high Si content when ashed at 500°C, namely around 85% and 57% respectively
- Coffee husk had a high K content when ashed at 500°C, namely 68%.
- Water hyacinth had unusually high contents of K and Cl when ashed at 500°C, namely around 25% of K and around 22% of Cl.
- The thermochemical behaviour of all the studied biomass types was clearly dependent on the combustion temperature.
- The thermochemical behaviour of rice husk and water hyacinth differed markedly from the other biomass types due to their extremely high ash content.

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Concluding remark

In the same way as the challenge of energy supply at a global scale is unlikely to be solved by a single energy production type, a single biomass based technology is unlikely to solve the challenges related to biomass utilization in countries with developing economies. Further knowledge regarding available biomass types is required in order to develop new techniques that can alleviate some of the environmental, social and health problems related to biomass utilization.

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Appendix 1

Table A1. Standards applied to the corresponding analysis.

Analysis	Standard method
Ash content at 550°C	SS-EN 14775
Gross heating value	SS-EN 14918
Net heating value	SS-EN 14918
Energy content	SS-EN 14918
Sulphur at 1350°C	EN ISO 16994
Carbon at 1050°C	EN ISO 16994
Nitrogen at 1050°C	EN ISO 16994
Hydrogen at 1050°C	EN ISO 16994
Chlorine content	SS 187154
Volatile matter	SS-EN 15148

Table A2. Compilation of the heating values.

Biomass type	HHV [MJ/kg]	LHV [MJ/kg]	LHV ash free basis [MJ/kg]
BG	18.28	16.97	17.73
CH	19.09	17.79	18.79
RH	14.47	13.43	18.20
SF	22.86	21.33	22.89
WH	14.26	13.22	17.44
CAS	19.11	17.78	18.14
GRE	19.83	18.48	18.70
SES	19.53	18.18	18.49
SES BK	19.30	18.08	19.59
SES ST	19.60	18.25	18.43

Table A3. Data obtained from the proximate analysis.

Biomass type	Ash	FC	Vm
BG	4.3	13.6	82.1
CH	5.3	20.3	74.4
RH	26.2	14.8	59
SF	6.8	13.5	79.7
WH	24.2	14.5	61.3
CAS	2	16	82
GRE	1.2	17.8	81
SES	1.7	18	80.3
SES BK	7.7	22.1	70.2
SES ST	1	16.7	82.3

Table A4. Results obtained from the Ultimate analysis.

Biomass type	Carbone	Oxygen	Hydrogen	Nitrogen	Chlorine	Sulphur
BG	46.8	42.7	6	0.2	0	0.02
CH	47.9	39.5	6	1.2	0.05	0.1
RH	36	32.4	4.8	0.5	0.09	0.04
SF	52.4	29.9	7.1	3.5	0.05	0.24
WH	37.5	28.1	4.8	2.2	2.9	0.29
CAS	48.2	43.2	6.1	0.4	0.05	0.02
GRE	49.6	42.6	6.2	0.3	0.02	0.04
SES	48.9	42.8	6.2	0.3	0.04	0.03
SES BK	49	36.7	5.6	0.9	0.04	0.09
SES ST	49	43.6	6.2	0.2	0.03	0.03

Table A5. Results obtained from the SEM-EDS analysis carried on the ashes.

	BG 500	CH 500	RH 500	SF 500	WH 500
K	11.42	67.88	4.76	29.39	25.44
Na	0.96	0.74	0.30	1.48	2.17
Ca	2.91	14.62	1.58	10.39	11.04
Mg	2.38	5.40	0.77	17.44	7.17
Al	15.90	0.20	2.53	2.39	7.14
Fe	5.78	0.99	0.79	2.04	2.72
Si	56.76	1.77	85.92	7.54	15.24
P	1.42	3.01	1.13	22.13	3.41
S	0.74	2.27	0.48	4.66	2.93
Cl	0.30	1.47	0.34	0.59	21.72

Table A6. Combustion process, devolatilization and char combustion phase times of the 5 agricultural residues and water hyacinth biomass types combusted at 700°C. The given values are the average value of three runs for each biomass type

Biomass type	Devolatilization time [s]	Char combustion phase time [s]	Combustion process time [s]
Bagasse	69	333	402
Coffee husk	61	329	390
Rice husk	65	525	590
Sunflower cake	74	266	340
Water hyacinth	70	416	486
Average Rice and WH	67.5	470.5	538
SD Rice and WH	3.5	77.1	73.5
Average others	68	309.3	377.3
SD Others	6.6	37.6	32.9
Average total	67.8	373.8	441.6
SD total	5	99.9	98.2

Table A7. Combustion process, devolatilization and char combustion phase times of the 5 agricultural residues and water hyacinth biomass types combusted at 950°C.

Biomass type	Devolatilization time [s]	Char combustion phase time [s]	Combustion process time [s]
Bagasse	43	206	249
Coffee husk	36.5	263.5	300
Rice husk	39	307	346
Sunflower cake	43	174	217
Water hyacinth	41	260	301
Average Rice and WH	40	283.5	323.5
SD Rice and WH	1.4	33.2	31.8
Average others	40.8	214.5	255.3
SD Others	3.8	45.4	41.9
Average total	40.5	242.1	282.6
SD total	2.8	52.3	50.2

Table A8. Combustion process, devolatilization and char combustion phase times of the 3 agroforestry trees pellets combusted at 700°C.

Biomass type	Devolatilization time [s]	Char combustion phase time [s]	Combustion process time [s]
Casuarina	80.1	297.9	378
Grevillea	75.2	354.8	430
Sesbania	73.2	319.8	393
Average	76.2	324.2	400.3
SD	3.6	28.7	26.8

Table A9. Combustion process, devolatilization and char combustion phase times of the 3 agroforestry trees pellets combusted at 950°C.

Biomass type	Devolatilization time [s]	Char combustion phase time [s]	Combustion process time [s]
Casuarina	46.8	201.2	248
Grevillea	46.2	208.8	255
Sesbania	48.1	211.9	260
Average	47	207.3	254.3
SD	1	5.5	6