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Characterisation of Biomasses for Their Valorisation in Energy and Biochar Production: Case of Cotton Stalks, Maize Rachis and Rice Husk

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Abstract

The main source of energy for most African families remains firewood. The exploitation of this resource is the main cause of accelerated environmental degradation with its consequences which are climate change and soil impoverishment. However, agricultural residues are often available and even abandoned in fields after harvest. In this regard, we have characterized three biomass with no economic value in order to use them for the production of biochar to improve soil quality while providing the energy necessary for household cooking. Our research was based on the following biomasses: cotton stalks, maize rachis and rice husks. The study made it possible to characterize the biomasses which could be used for combustion and/or pyrolysis. From the results obtained, we could observe a high ash content in the rice husk (24.21%) against 2.41% for cotton stalks and 2.00% for maize rachis. These results influence the calorific value of the rice husk, thus allowing it to be used matter in pyrolysis and not in combustion. In addition, cotton stalks and corn rachis can be used both as fuel and as biomass to be pyrolyzed.

Keywords

Characterization of Biomass, Energy, Pyrolysis, Combustion, Biochar

1. Introduction

In many developing countries, and more especially in Burkina Faso, the main source of energy for cooking comes from wood from forests. This pressure on wood leads, among other things, not only to deforestation, but also to soil degradation. The importance of forests for preserving the balance of ecosystems

and managing soil fertility is well known and represents a major challenge for future generations. By way of alternative, biomass is a promising resource to meet growing energy needs of industrialized and developing countries [1]. Several thermochemical studies have been carried out on different biomasses, especially on cotton stalks [2], rice husks [3], Sida cordifolia [4], casava bagasse [5], plumbing waste [6], cashew shells [7], etc. The results obtained for all of these biomasses are satisfactory, hence the interest in upgrading its biomass. The conditions of use differ from one biomass to another depending on the results expected by each user. Most of the conversions studied were conducted in modern stoves where the parameters are well controlled. Unfortunately, these modern stoves are not accessible to small producers in developing countries because of the high cost of the equipment. However, the latter have biomass with no economic value that could be used in combustion. Most biomasses are often used as fuel for cooking, for charcoal production or left in the fields. Biomasses can also be converted into biochar to improve agricultural soils. Biochar is biological charcoal obtained by pyrolysis in a stove in the absence or with little oxygen. Numerous studies have shown that biochar improves agronomic efficiency and reduces nutrient losses from plants. Its capacity to adsorb soluble organic matter, gases and inorganic nutrients makes it an ideal habitat for microorganisms, especially bacteria, which colonize it to develop and reproduce [8] [9]. Biochar therefore effectively contributes to improving agricultural yields. However, the quality of biochar depends not only on the parameters influencing pyrolysis, but also on the biomasses used for its production.

The main objective of this study is to characterize the different biomasses available for use. These are cotton stalks, corn rachis and rice husks. This characterization will make it possible to understand their influence on combustion, as well as the quantities of energy available, that is to say, the lower heat value (LHV) that the fuels derived from these biomasses can provide. Unlike fossil fuels, biomass-based fuels come in many forms and have features that can vary greatly [10] from fuel to fuel. Thus, a study will be made to show how each biomass loses mass through a Thermogravimetric Analysis (TGA); this will help assess the pyrolysis time depending on the heating rate. The results could be used to dissociate biomasses that can be used as pyrolysis fuels from those that will be pyrolyzed to obtain biochar. These biomasses will be used in a multifunctional artisanal *Anila-type* stove [11] which simultaneously enables the provision of the energy necessary for cooking and the production of biochar for soil improvement.

2. Materials & Method

2.1. Material

2.1.1. Biomasses
The biomasses used in this study are biomasses with no economic value, that is to say, they are neither in competition for food needs nor directed for other use-

ful purposes. Therefore, they are left in the fields after harvest. CP Kpadé *et al.*, [12] have shown that most cotton producers in the sub-region already convert biomass using different thermochemical processes to obtain energetic charcoal or using direct heating for cooking and even gas to make the engines run. In the case of our study, cotton stalks (Figure 1(a)) and maize rachis (Figure 1(b)) not only serve as fuel to initiate pyrolysis, but also constitute a raw material to be pyrolyzed. As for the rice husk (Figure 1(c)), it is only a raw material to be pyrolyzed.

2.1.2. Equipment Used

The equipment used in this study are:

- Restch knife mill;
- Porcelain cricibles 15 cm deep;
- Precision analytical balance 0.1 mg with a range of 0.01 à200 g;
- Sieve with 800 μm mesh opening;
- Ventilated stove allowing the temperature to be set at 105˚C;
- Muffle furnace allowing the temperature to remain at around 815˚C;
- Desiccator to isolate the sample from ambient humidity in the laboratory;
- US 030 adiabatic calorimeter.

2.2. Method

2.2.1. Immediate Analysis

The biomass samples used in this study were previously dried in the sun, crushed with a US034 restch knife mill and sieved with an 800 μm sieve for analysis of particle size before their characterization. The crucibles and the balance are materials which were used in all the experiments.

1) Moisture content

The samples, crushed and sieved beforehand, are dried in an oven at a temperature maintained at 105˚C ± 2˚C until a constant mass is obtained. The moisture is calculated in accordance with the FO 004 form (Excel spreadsheet) available at the laboratory where the tests took place. The maximum acceptable difference between the results of two tests carried out simultaneously or rapidly one after the other, by the same operator, must not be greater than 5% of the mean value of the two measurements. The moisture content h [13] is given by the following relation (1).

(a) cotton stalks   (b) maize rachis   (c) rice husk
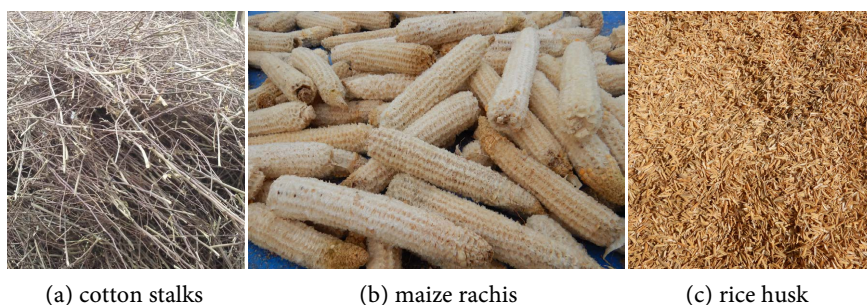
Figure 1. Biomasses used.

$$h = \frac{m_2 - m_3}{m_2 - m_1} \times 100 \tag{1}$$

with:

m_1 as the mass of the empty crucible (g), m_2 the mass of the crucible with the sample before drying (g) and m_3 the mass of the crucible with the sample after drying (g).

2) Higher Heating Value

The Higher Heating Value (HHV) [13] is measured using an adiabatic calorimeter. The Higher Heating Value (HHV) is the amount of heat, in joules per gram, released after a unit mass of fuel is completly burned by recovering the latent heat of vaporisation (fully condensed) and of the other products of combustion. Inigtion is ensured by a wire placed between two electrodes, the initial length (l_i) of which is known. This ignition wire, the heat of combustion of which is known, burns once in contact with the sample. At the end of the experiment, we measure the length of the remaining wire which we denote by l_f.

The HHV is given by relation (2):

$$\text{HHV} = \frac{\left[K_1 \times E_{cal} \times (T_m - T_i) - K_1 \times E_{pt}(l_i - l_f) \right]}{m_{ech}} \tag{2}$$

with:

K_1 = 4.1855 J/cal the calorie conservation factor in Joules, E_{cal} = 2674 Cal/°C is the calorimetric equivalent of the calorimeter of the bomb, of its accessories and of the water introduced into the bomb in cal/°C, T_m et T_i the maximum and initial temperature in °C, E_{pt} = 2.3 cal/ cm the heating value of platinum, l_i et l_f the initial and final length in cm and m_{ech} the mass of the test portion to be analysed in g.

3) Lower Heating Value

The lower heating value (LHV) [13] is deduced from the higher heating value (GCV) and the fuel moisture content. The maximum acceptable difference between the results of two tests carried out simultaneously or rapidly one after the other, by the same operator, on the same sample must not be greater than 0.5% (repeatability). Relation (3) gives the LHV:

$$\text{LHV} = \text{HHV} - \left[\frac{(E_{cond} * K_2 * H_{ech})}{100} + \frac{(E_{cond} * W)}{100} \right] \tag{3}$$

Avec:

E_{cond} = 2511 J/g the heat of water condensation, K_2 the proportionality factor which is equal to $K_2 = \dfrac{\text{mass of hydrogen present}}{\text{mass of water formed}} = 8937$, H_{ech} [13] the hydrogen content of the sample in % given by Equation (3) and W the humidity content of the sample.

The hydrogen content of a sample can be determined from relation (4):

$$H_{éch} = \frac{H_{anhydre} * (100 - W)}{100} \tag{4}$$

4) Volatile matter content

The experiment for determining the volatile matter content V_s [13] is carried out by carbonising (in a furnace) a sample previously dried at 105°C in an oven. The volatile matter content is then deduced from the anhydrous sample mass loss. The volatile matter content, denoted by V_s, expressed as a percentage of the dry matter, is calculated using Equation (5):

$$V_s = \frac{m_2 - m_3}{m_2 - m_1}$$ (5)

With:

m_1 the mass of the empty crucible (g), m_2 the mass of the crucible with the anhydroue sample (g) et m_3 the mass of the crucible and the ashy residue (g).

The maximum acceptable difference between the results of two tests carried out simultaneously or rapidly one after the other, by the same operator, on the same sample must not be greater than 0.3% of volatile matter for volatile matter contents less than 10% and 0.5% volatile matter contents greater than or equal to 10%.

5) Ash content

The method used for this measurement is to incinerate an anhydrous sample in a muffle furnace. This involves heating the sample first at 250°C for 1 hour, then at 550°C for 1 hour and finally 815°C for 2 hours. The ash content C_e [13] is thus obtained by Equation (6):

$$C_e = \frac{m_3 - m_1}{m_2 - m_1}$$ (6)

With:

m_1 the mass of the empty crucible (g), m_2 the mass of the crucible with the anhydrous sample (g) et m_3 the mass of the crucible with the ash after complete combustion (g).

The maximum acceptable difference between the results of two tests carried out simultaneously or rapidly one after the other, by the same operator, on the same sample must not be greater than 0.2% ash, for ash contents less than or equal to 10% and 2% ash, for ash contents greater than or equal to 10%.

6) Fixed carbon content

The fixed carbon content CF [13] is obtained from the volatile matter content and the ash content. It is expressed as a percentage and is calculated by equation (7):

$$CF = 100 - \left(V_s + C_e \right)$$ (7)

With:

V_s denotes the percentage of volatile matter and C_e the percentage of ash.

2.2.2. Thermogravimetric Analysis

The analyzer used is an *A6 evolution* thermogravimetric analyzer. The principle of the experiment consists of measuring the variation in the mass of a sample

placed in furnace under nitrogen. The change in mass is measured as a function of time when the sample is subjected to a given temperature or temperature profile. The mass of the sample used for the experiment is 20 mg. The thermogravimetric measurements were carried out as follows:

- The sample is first subjected to a temperature ramp ranging from 25 to 800˚C for a heating rate of 10˚K/min. This phase lasts 75 min;
- The sample is then exposed to a temperature plateau of 800˚C for 30 min;
- Finally, the furnace undergoes a cooling phase to bring it back to room temperature.

This experiment thus makes it possible to establish the kinetics of mass loss of a sample according to the temperature to which it is subjected.

3. Results & Discussions

3.1. Immediate Analysis and the Lower Heating Value (NCV)

Table 1 presents the results of the immediate analysis carried out on the cotton stalks, the maize rachis and the rice husk as well as the heating value of these three biomasses.

We notice that the rice husk has a very high ash content of around 24% (Figure 2) which decreases its LHV (14.11 MJ/kg). This low heating value shows that the rice husk is not suitable as a pyrolysis fuel. In addition, the heat produced during pyrolysis is not sufficient for drying the rice husk before pyrolysis. As a result, the condensable gases released in the pyrolysis chamber condense and turn into tar which settles on the biomass waiting to be pyrolyzed. This tar slows the pyrolysis of the biomass if the heat is not sufficient to crack it which can cause the presence of the underlined unburnt in the biochar of the rice husk.

As for maize rachis and cotton stalks, unlike rice husks, they have a low moisture content of around 6% and a low ash content (around 2%). The value of their LHV (18 MJ/Kg) shows that they can be used as fuel (Figure 2) and as biomass to be pyrolyzed.

Based on the results obtained in Table 1, maize rachis provides more heat than cotton stalks and rice husks. In addition, they release more volatile matter about 79% than the other two biomasses. These released volatiles are combustible gases and can in turn burn to aid combustion. The results of the fixed carbon and volatile matter content of cotton stalks are close to that of the biomass study by S. Zellagui (2017) [14] [15], that of J.-P. Tagutchou and P. Naquin [16], on raw cashew shells which gives respectively 19.4% and 80.6%, that of E. Daouk [17] on pine wood which gives respectively 83.3% and 15.4%. Rice husk have a low volatile matter content as compared to cotton stalks and maize rachis (Figure 2).

3.2. Thermogravimétri Analysis (ATG)

Figure 3 shows the mass loss curves as well as their derivative with respect to time during biomass pyrolysis (Figure 3): (a) cotton stalks; (b) corn rachis; (c) rice husk.

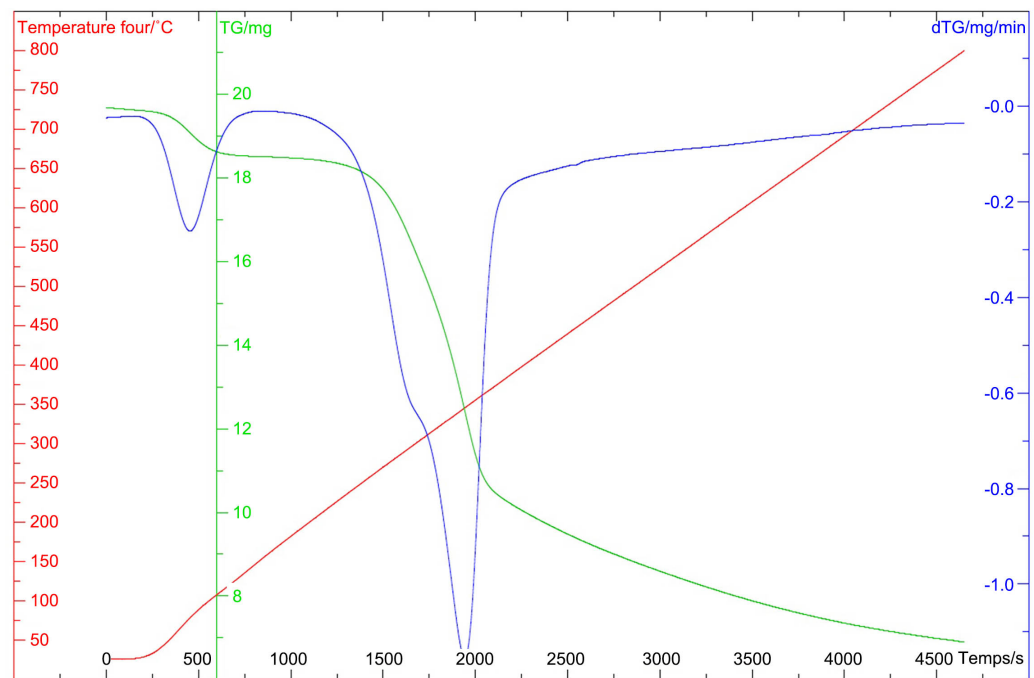Table 1. Immediate analysis of biomasses and their heating value.

Biomasses	Moisture %	Volatile matter %	Ash content %	Fix carbon content %	LHV MJ/kg
cotton stalks	6.2190	76.5470	2.4144	21.0385	18.77
maize rachis	5.7109	78.9888	2.0062	19.0049	17.99
rice husk	5.17687	58.6736	24.2125	17.1137	14.11
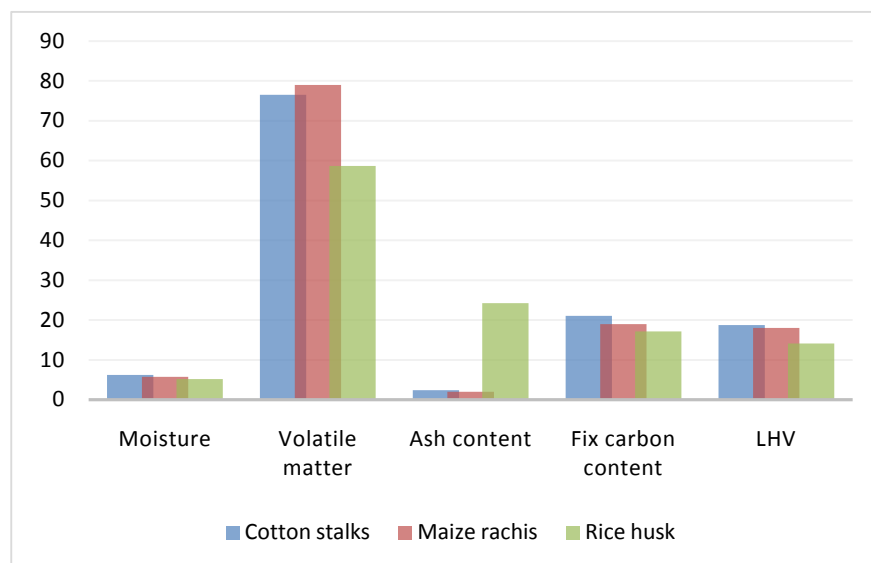
Figure 2. Immediate analysis and low heating value diagram
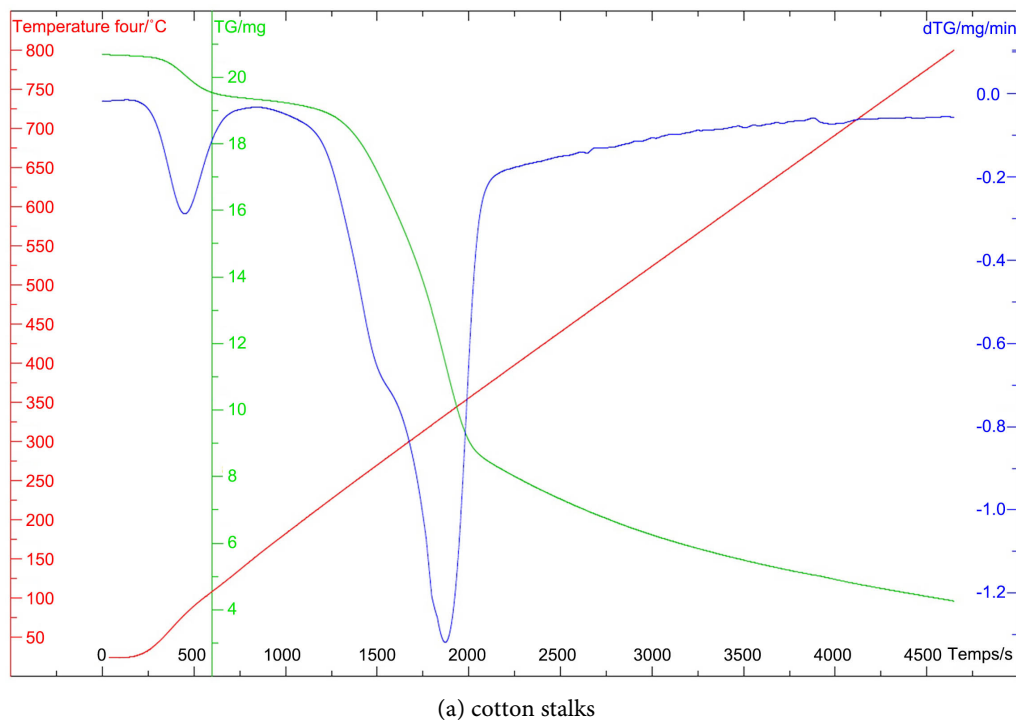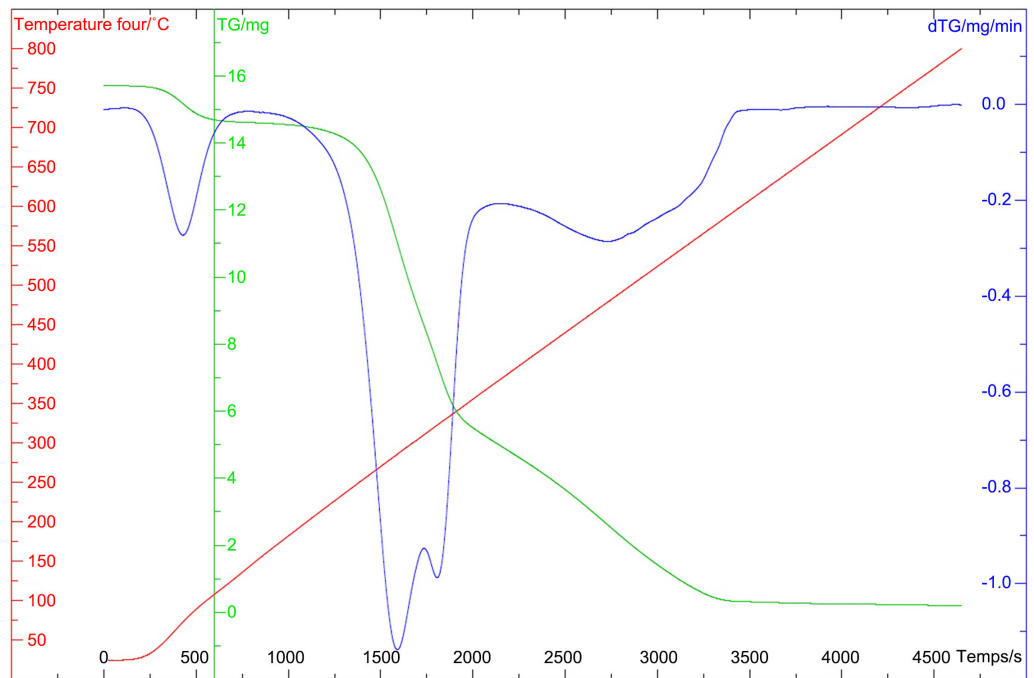
(a) cotton stalks

(b) maize rachis

(c) rice husk

Figure 3. Thermogravimetric analysis of cotton stalks, maize rachis and rice husk.

This study was conducted over an operating temperature range going from 25 to 800˚C for a maximum duration of 1 h 20 min. It can be seen that the higher the temperature, the greater the loss of mass per unit of time. Based on **Figure 3**, in the presence of oxygen, the curves of mass loss and its derivative with respect to time can be divided into three phases: drying, pyrolysis and oxidation of bio-

char. The first phase, which lasts 20 minutes, is said to be endothermic and corresponds to the drying of the biomass for a temperature less than or equal to 250˚C. The rate of mass loss is not very high because of the influence of moisture contained in the different biomasses. Peaks in the rate of mass loss are observed at 0.3 mg/min. The second exothermic phase shows a rapid decrease in the loss of mass for 10 minutes. When the temperature is between 250˚C to 350˚C, there is a release of volatile matter which justifies the very high rate of mass loss which can reach a threshold of 1.3 mg/min. The last phase, which is also exothermic, represents the oxidation of the biochar followed by detachments of some volatile matter. This phase takes place when the temperature is between 350˚C and 700˚C. The behavior of the loss of mass and of its derivative with respect to time is similar to the results obtained on pine wood by Y. Su *et al.* (2012) [17]. The separation between the phases is characterized by an inflection point for the mass loss curve and by the presence of two peaks for the derivative. The first peak, attributed to dehydration and the second peak, at higher temperatures, represents the pyrolysis of biomass. By comparing the results obtained on the three biomasses, we see that the maize rachis reach their maximum first (about 1500 seconds) before the cotton stalks and the rice husk which are around 1900 seconds.

4. Conclusion

The characterization of biomasses (cotton stalks, corn rachis and rice husks) highlights the influence of ash content on heating value. This allows judicious choices to be made on the materials to be pyrolyzed and those which must provide the energy required for the pyrolysis. These results show a high ash content for the rice husk, which influences its heating value. Therefore, the rice husk is not suitable for combustion but can be used as biomass to be pyrolyzed if the heat input is sufficient to crack the tar condensed on the biomass waiting to be pyrolyzed. As for cotton stalks and corn rachis, they show good results for combustion and pyrolysis. Indeed, their heating value is quite close to that of wood found in the literature. They have a high level of volatile matter which are combustible gases that can contribute to the production of heat. The measurement of the fixed carbon content shows that in addition to the energy supplied during pyrolysis through the fuel gases, it is possible to obtain good quality coal at the end of the process. This coal "called biochar" produced under certain biomass pyrolysis conditions can be used to amend the soil. It is therefore necessary to consider an experimental study to determine the parameters that govern pyrolysis in order to obtain optimal biochar for thermal energy production and soil fertility management applications.

Acknowledgements

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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