Experimental study of biochar and energy production in a multifunction family oven

Comment [IA1]: The titlemaybechangedinto « Temporal temperatureevolusionduring the pyrolisis of cottonstalks, corn stalk and ricehuskusingmultifunctionfamilyoven »

Abstract

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The multifunctional family oven is an oven able to produce simultaneously biochar for soil improvement and energy for cooking. However, the quality of the biochar produced depends not only on the selected biomass but especially on the pyrolysis temperature which is a very important parameter. This experimental study aims to understand the functioning of the oven with respect to its biochar production and the pyrolysis duration. To carry out our study, K-type thermocouples were used to measure the temperature on the different walls and chambers of the oven. Cotton stalks, corn stalks and rice husk were used for this study. The results obtained showed that the cotton stalks reached the maximum pyrolysis temperature at 430 °C around 1700 s. This temperature remained constant for 1500 s before decreasing to mark the end of pyrolysis. As for the corn husks, they reached their maximum average pyrolysis temperature at 470 °C after 3000 s. The rice husk reached a maximum pyrolysis temperature of 420 °C after 3500 s. A comparative study of the temperature curves of the three biomasses revealed that cotton stalks pyrolyze faster with short time than the other two biomasses. The results obtained on the pyrolysis temperature, corroborate those of the literature from which the multifunctional family oven produces a quality biochar. The maximum temperature of combustion which starts the pyrolysis is about 800 °C and can last for 1h30 min. Thus, this heat is valued by the cooking of different dishes of the country.

Key words: multifunctional oven, biochar, energy, agricultural residues.

1. Introduction

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Burkina Faso is a landlocked Sahelian country in West Africa. Most of its population, 85%, lives from agriculture [1]. For some time, the country has been experiencing increased degradation of its natural resources, particularly the soil [2]. By soil degradation, we mean the loss of its potential, especially the depletion of soil nutrients [3]. Indeed, this soil degradation is caused on the one hand by the effects of climate change and on the other hand by poor farming practices, which have resulted in desertification and the continued decline in soil fertility ([4]; [5]; [6]). The significant decline in agricultural yields is therefore noted among producers. To obtain good yields, farmers use chemical fertilizers and sometimes compost to adequately feed their crops [2]. However, it is necessary to recognize the drifts noted in the use of fertilizers such as the non-respect of the doses, the always late contributions and without burying in the grounds [2]. These deviations have as a consequence, the inefficiency of these fertilizers which constitutes a loss of money and a source of environmental pollution ([7]; [8]). However, farmers have a large quantity of agricultural residues, most of which are little used after the harvest (cotton stalks, maize stalks, rice husks, groundnut shells, cashew shells, etc.). These residues, which have no market value, are burned in order to free the fields for new planting. Consequently, Burkina Faso's agriculture faces an important challenge which is to change or evolve the mode of land use in order to ensure a more sustainable, positive and fair future [9]. Moreover, the valorization of agricultural residues can contribute in a decisive way to ensure the maintenance of the fertility of cultivated soils [10]. Several studies have shown that biochar is an alternative for restoring soils and improving agricultural yields [11]. By using biochar as an amendment, biochar is used for carbon sequestration, enhancement of soil physicochemical properties, restoration of arid soils, water retention,

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absorption of pollutants and plant nutrients [12], [13], [14]. In addition, the quality of biochar depends on the operating conditions of pyrolysis such as temperature [15]. A good operation of the oven allows to obtain an optimal biochar. However, its production remains an important issue for its popularization in southern countries and a global issue for the environment. Recent artisanal pyrolysis technologies exist, but the scientific description of the pyrolysis process during their operation is not yet well established. It is therefore necessary to make a scientific approach on the technique of biochar production of an artisanal oven. The device used in this study is a multifunctional family oven with a double objective, namely, an alternative technique for the production of biochar and the energy needed for household needs [16]. Therefore, this study aims to understand the operation of the family oven during pyrolysis to ensure the quality of the biochar produced. In the case of this study, cotton stalks, maize stalks and rice husk are used. The knowledge of some properties of these residues facilitated their use [17]. To carry out our study, K-type thermocouples were installed on the walls and in the chambers of the kiln on three different levels depending on the height. The results obtained will allow the optimization of the production as well as the quality of the biochar.

2. Material

2.1.Description of the experimental device

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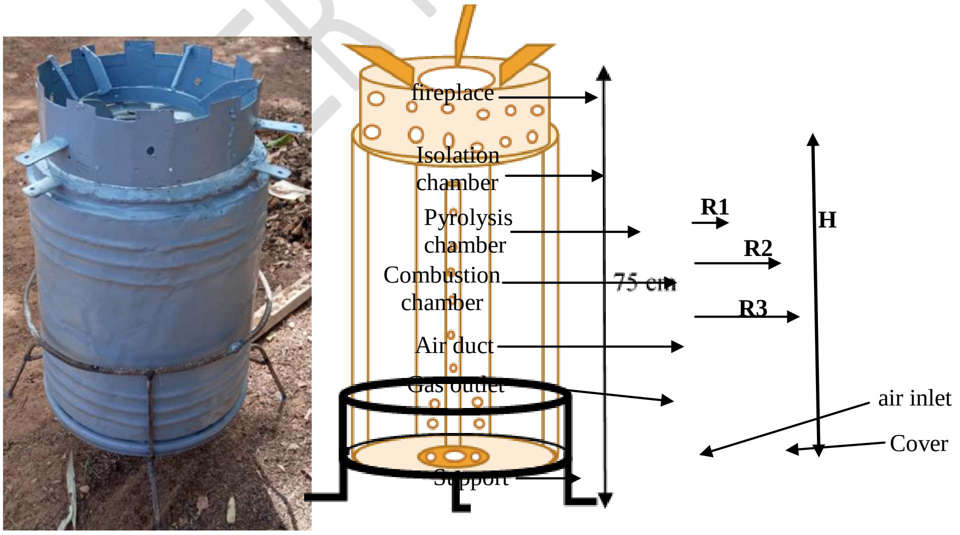
The device used in this study is a multifunctional family oven that allows to produce biochar and to valorize the energy produced through cooking (figure 1.a). It consists of three parts: the combustion chamber, the pyrolysis chamber and the isolation chamber which is hermetically sealed with air (figure 1.b). The pyrolysis chamber receives the biomass to be pyrolyzed and the combustion chamber receives the fuel to be burned. Indeed, the different chambers which constitute the furnace are designed so that the heat exchange between the combustion chamber and the pyrolysis chamber is optimal. Also, the central cylinder allows the syngas (released pyrolytic gases) to be channeled back into the combustion chamber, thus creating a snowball effect. The isolation of the device from the outside environment is achieved by a layer of air surrounding the pyrolysis chamber, which ensures safety during use and reduces heat loss from the pyrolysis chamber.



(a) (b)

Figure 1: Presentation (a) and description (b) of the multifunction family oven

2.2.Type K thermocouple

The main sensors used are type K thermocouples (figure 2) with an extension cable made of ceramic fiber wires that can withstand a continuous temperature of more than 1000 °C. Indeed, a thermocouple is a sensor that mainly uses the Seebeck effect to obtain a temperature measurement

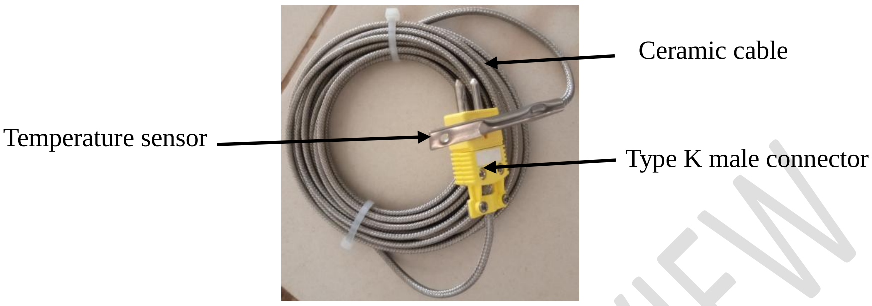


Figure 2: Type K thermocouple

2.3.Biomass used

For the operation of the multifunctional family stove, the biomasses used are available agricultural residues with no market value that are not highly valued and that do not compete with the animal feed sector. These are: cotton stalks, maize stalks and rice husks. These agricultural residues are generally left in the fields. Cotton stalks (Figure 3.a) are left behind after flower harvesting, and maize stalks (Figure 3.b) and rice husks (Figure 3.c) are obtained after ginning. The use of these residues will help protect the environment by reducing excessive logging and deforestation. In this study, cotton stalks and maize stalks are used as fuel to initiate pyrolysis, not only because of their size, but also because these residues have a lower calorific value and an ash content that is very favorable to combustion. Tarpilga M.C. et al [17] have characterized these residues. These results showed that the calorific value (PCI) of cotton stalks is 18.77 MJ/kg and its ash content is 2.41%. Corn stover has a heating value of 17.99 MJ/kg with a low ash content of 2%. Corn husks are used as fuel and also for pyrolysis. However, rice husk has a smaller particle size and can block the air inlets of the combustion chamber, so it cannot be used as fuel. Also, it has a low PCI of about 14.11 MJ/kg and a very high ash content of about 24.21%.

(a) (b) (c)

Figure 3: Cotton stalks (a), maize stalks (b), rice husk (c) used for combustion and pyrolysis

3. Method

3.1.Principle of operation of the oven

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The use of the multifunctional oven requires a minimum of knowledge. First of all, the pyrolysis chamber is loaded with the pyrolysis biomass (figure 4.a) and closed hermetically with the lid before loading the combustion chamber with the fuel to be burned (figure 4.b).

Finally, the whole device is placed on the support with its hearth to put the pot (figure 4.c). The fuel is ignited and the pyrolysis process begins (figure 4.d).

Figure 4: Principle of use of the multifunctional family oven

According to the literature, biochar production technologies generally include pyrolysis, gasification, hydrothermal carbonization, flash carbonization and baking carbonization [19], [20]. Moreover, the principle of operation of our oven, refers to an indirect slow pyrolysis seen that the pyrolysis chamber receives heat by a thermo-physical transfer through an internal wall (Pi).

According to Braga et al. (2014) [21] , showed that biomass can be converted to charcoal by the pyrolysis method. However, during this conversion process, biomass releases volatile materials in the form of condensable gases (bio-oil or tar) and non-condensable gases (syngas or biogas) leaving the solid carbonaceous product called biochar [22]. The gases produced in the pyrolysis chamber of the multifunction family furnace are channeled to the gas outlet to contribute to the combustion (Figure 5). The tars are cracked into light combustible gases when the temperature is above 500 °C [23]. The airline ensures that the oxygen rises to the interior of the combustion chamber. As soon as there are no more pyrolytic gases to be released, the flame is extinguished and we move on to smothering the combustion chamber with sand. This will prevent air from entering the pyrolysis chamber to continue the combustion.

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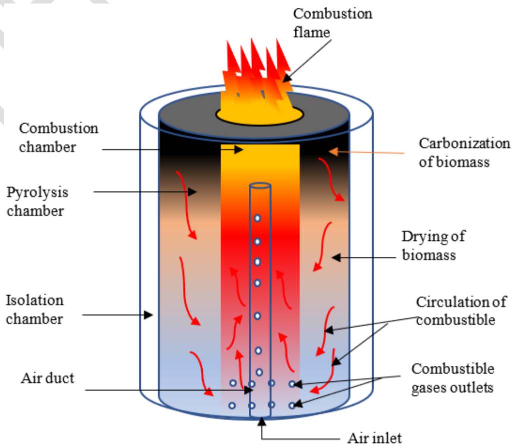

Figure 5: Operation of the family oven during pyrolysis

It is advisable to wait for the oven to cool down (about 20 minutes) before opening the pyrolysis chamber, otherwise the gases remaining in this chamber may ignite when in contact with the air. The pyrolysis time varies between 1 h 15 min to 1 h 30 min depending on the type of biomass used or the quantity of load. This time allows to bring the necessary heat to the cooking of the food. Equation (1) describes the pyrolysis conversion of biomass [24]:

$$CH_yO_x \rightleftharpoons \frac{x}{1+0{,}5y}CO + 0{,}5y\frac{x}{1+0{,}5y}H_2O + \left(1-\frac{x}{1+0{,}5y}\right)\left(1-\frac{y}{4}C+\frac{y}{4}CH_4\right) \quad (1)$$

Figure 6 shows the flow chart of the furnace operation during pyrolysis.

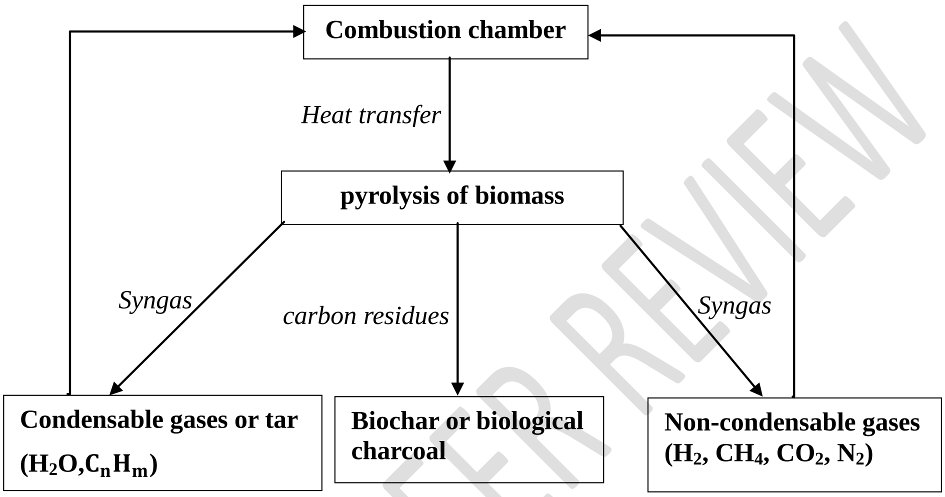

Figure 6: Summary diagram of the operation of the multifunction family oven

3.2.Temperature gradient measurements

For this study, three levels were explored (N1, N2 and N3) along the axis (Figure 7):

- N1: top of the furnace,
- N2: middle of the furnace,
- N3: bottom of the furnace

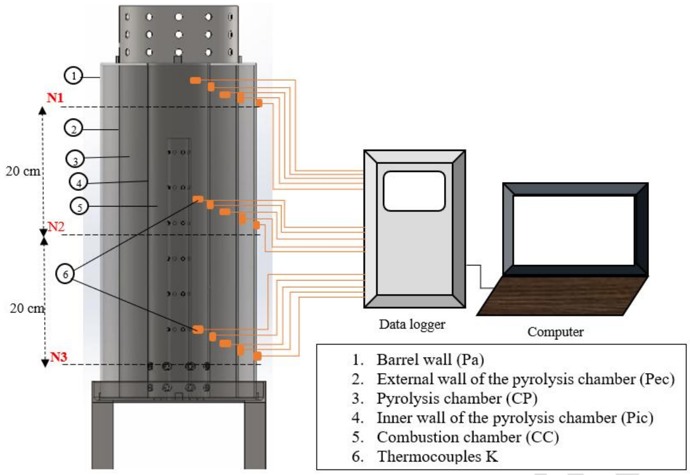

Figure 7: Experimental study of the furnace

At each level indicated, we placed K-type thermocouples at five (5) different locations (Figure 7) which are:

The barrel wall or ambient wall (Pa) (the wall in contact with the outside environment),

The external wall (Pec) (wall separating the pyrolysis chamber and the isolation chamber),

The pyrolysis chamber (CP),

The inner wall (Pic) (wall separating the combustion chamber and the pyrolysis chamber),

The combustion chamber (CC).

The distances between the levels N1 and N2, and N2 and N3 are 20 cm. N1 is located at 3.5 cm from the top of the furnace and N3 at 3.5 cm from the base. The measured temperatures are recorded in a data logger (model MS6D) before being transferred to a laptop computer for processing (Figure 7).

To ensure repeatability and reproducibility of the experiments for each biomass used, the temperature averages were calculated to build the different profiles.

3.3.Experimental condition

In order to properly conduct this experimental study, we made the following assumptions:

- thermocouples are installed on the inner (Pic), outer (Pec), and outer walls of the furnace (Pa) as well as in the combustion and pyrolysis chambers,
- the corn stover is used as fuel for the pyrolysis of the three biomasses,
- the results retained for this study are those from level 2 (middle) of the furnace,
- the temperature profiles are the average temperatures of five tests of the furnace operation,
- the fumes analyzed are CO_2, CO, CH_4 and H_2 from cotton stalks and corn stalks, which are the two fuels used.

4. Results and discussion

4.1.Temporal evolution of the temperature during the pyrolysis of cotton stalks

Figure 8 shows the temporal evolution of the temperature of cotton stalks.

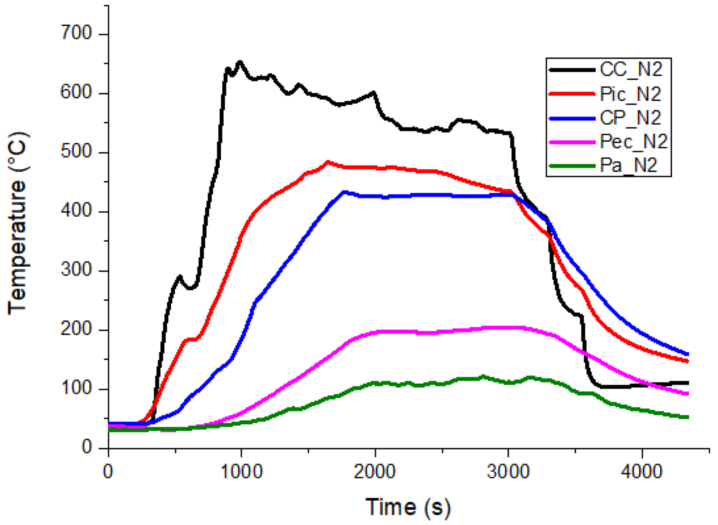

Figure 8: Time course of temperatures during pyrolysis of cotton stems.

The temperature curves evolve together at a temperature below 50 °C for 250 s before growing separately. This delay in the temperature rise, especially in the combustion chamber, shows that the combustion had not reached this level of the furnace. However, as soon as the combustion starts at this level, there is a rapid rise in the temperature profile of the combustion chamber followed by that of the inner wall (Pic). The average temperature of the pyrolysis chamber reaches (250 °C) around 1200 seconds (s) and evolves progressively until reaching a maximum temperature of 400 °C around 1700 s. This temperature remains constant during 1500 s before decreasing to mark the end of the pyrolysis. The abrupt drop of the temperature curve of the combustion chamber observed, is due to the fact that the combustion chamber is choked with sand at the end of the pyrolysis in order to prevent the air from penetrating in the pyrolysis chamber. This temperature drop leads to a rapid decrease in the temperature of the pyrolysis chamber and the furnace walls.

The maximum temperature of the outer wall of the furnace (Pa) is about 100 °C. The high value of this temperature shows that there are huge heat losses through the furnace walls. This result corroborates the results of the simulations which showed that the insulation with air was not very efficient. In fact, the external wall temperatures are well above the international standard for the protection of individuals against burns, which is 60 °C.

4.2.Average temperature profile of corn cobs

Figure 9 shows the temporal evolution of temperature during pyrolysis of corn cobs.

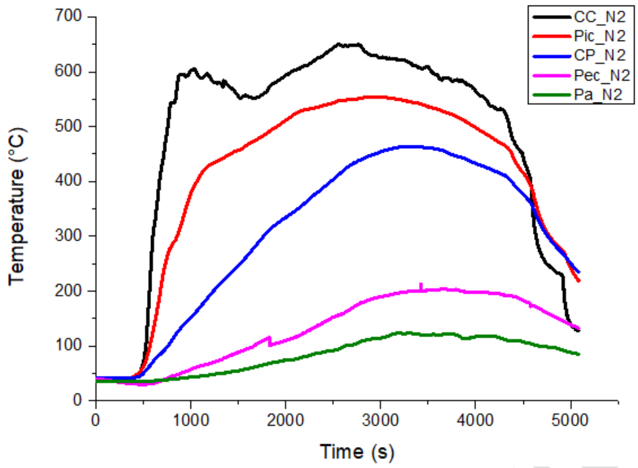

Figure 9: Temporal evolution of the temperatures during the pyrolysis of corn cobs

When the combustion reaches level 2 of the furnace, the temperature of the combustion chamber (CC) rises sharply and reaches a maximum of 600 °C. Likewise, the temperature of Pi increases with the temperature of CC but does not reach its maximum. This evolution of the Pi temperature causes the progressive heating of the corn cobs to be pyrolyzed which reaches the value of 250 °C around 1500 s before the maximum temperature of 470 °C. The maximum temperature reached shows that we will obtain biochar [25] and especially with a long residence time of about 5000 s, all the stalks will be pyrolyzed. This is true especially since corn cobs release more volatile matter which will burn in the combustion chamber to contribute to the pyrolysis.

4.3.Temporal evolution of temperature during pyrolysis of rice husk

The results in Figure 10 show the pyrolysis temperature of the rice husk.

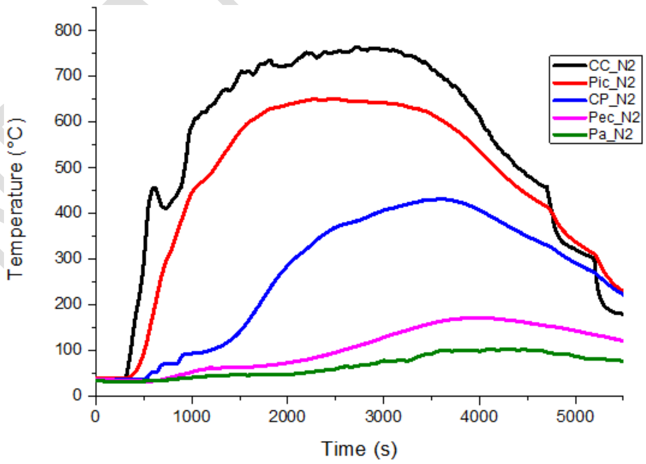

Figure 10: Temporal evolution of the temperatures during the pyrolysis of the rice husk

In Figure 10 as in the two previous ones (Figure 8 and Figure 9), the curves have the same gaits. The temperatures of the combustion chamber and of the inner wall of the pyrolysis chamber increase rapidly until 750 °C and 600 °C respectively. The temperature of the pyrolysis chamber evolves slowly and reaches its maximum at 420 °C around 3500 s. Rice husk has a low PCI and a high ash content, which makes it difficult to pyrolyze. Unpyrolyzed rice husk is observed in the biochar produced. Its pyrolysis is not as good as the previous two.

4.4.Comparative studies of pyrolysis temperature profiles for the three biomasses

Figure 11 shows the variation of the average temperature in the pyrolysis chamber for the three biomasses selected for this study.

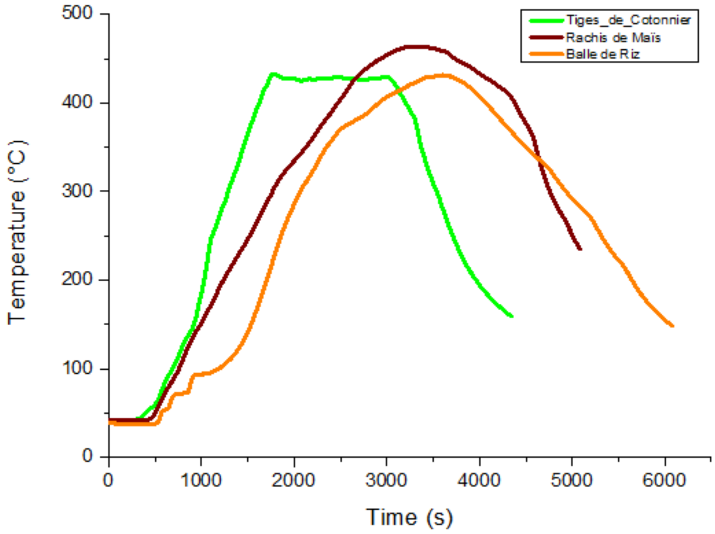

Figure 11: Comparison of pyrolysis temperature profiles for cotton stalks, corn stalks and rice husk

During pyrolysis, the volatile materials released are burned. This combustion contributes to the rise of the pyrolysis temperature. Once the pyrolysis is finished, there is no more emission of volatile matters which leads to the fall of the temperature. Indeed, the results show that during these various tests, the corn stalks allow to obtain the highest pyrolysis temperatures (470°C) with a rather long residence time. As for the cotton stalks, they pyrolyze very quickly with a very short residence time (3300 s) than the two other biomasses and reach a maximum temperature of 430°C. The rice husk pyrolyzes very slowly with a residence time of 4000 s and reaches a maximum temperature of 430 °C.

4.5.Biochar produced by the multifunctional family stove

Figures 12.a, 12.b, 12.c show the biochar obtained from cotton stalks, maize stalks and rice husk, respectively. Biochar is different from charcoal fuel or other carbon-based products in that it is intended to be used as a soil amendment in the context of the fertility issue [26]. It is produced at more than 400 °C while fuel coal is produced at less than 300 °C. Biochar after releasing the volatile matter as gas, becomes very porous. This is why biochar has a great capacity to absorb water and a large capacity to lodge nutrients in its pores to release slowly to the benefit of plants. As for the combustible charcoal commonly called charcoal, it still contains residues of volatile matter that allows it to burn. Physically, biochar has a low density. Used as a soil amendment, it also contributes to carbon sequestration [12]. Biochar improves crop yields. Unburnt material is present in rice husk biochar (Figure 12.c), but this does not change its quality because it can compost easily by attracting more bacteria to enrich the biochar. The unburnt material can easily decompose and attract microorganisms that can immediately move into the pores of the biochar to feed the plant. The yield of biochar produced by the multifunctional family oven is 25% for cotton stalks, 28% for corn stover and 29% for rice husk.

(a)

(b) (c)

Figure 12: Cotton stalk biochar (a), corn stover biochar and rice husk biochar (c)

Conclusion

The experimental study consisted in presenting the temporal evolution of the temperature of the different parts of the multifunction family oven. The results obtained on the three biomasses show that the device works very well. Cotton stalks, maize stalks and rice husks were used for this study. The results obtained showed that the cotton stalks reached the maximum pyrolysis temperature at 430 °C around 1700 s. This temperature remained constant for 1500 s before decreasing to mark the end of pyrolysis. As for the corn husks, they reached their maximum average pyrolysis temperature at 470 °C around 3000 s before decreasing. As for the rice husk, its maximum pyrolysis temperature was reached at 420 °C around 3500 s. The comparative study showed that cotton stalks pyrolyze faster with a short time than the other two biomasses. The pyrolysis temperature results corroborate those of the literature from which the biochar produced is a quality biochar. The results also showed that the maximum temperature of combustion is about 800 °C. This temperature therefore predicts that the various cooked dishes are quickly cooked in a short time.

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