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ENERGY ASSESSMENT FROM SUGARCANE TORRIFIED ON N₂ AND CO₂ ATMOSPHERE

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Abstract. Biomass has a low energy density and its direct use in conventional combustion systems faces major challenges. To increase the energy density, recent studies suggest the torrefaction of biomass as a simple, inexpensive and easy to implement process; possessing great potential for its industrial insertion. Torrefied biomass (biochar) is not only cheap and environmentally friendly, but also, it is the only biofuel that could be burned directly in conventional combustion systems. However, there is a lack of technical information on the quality of biochar as an alternative biofuel. This lack of knowledge can lead to the production of biochar not suitable for burning, increasing problems related to the production of slag and scale and reducing combustion efficiency. In Brazil, there are three lignocellulosic biomasses relevant to the energy sector (i.e. sugarcane) and the evaluation of the value added to the application of biochar as biofuel could provide some advantages and is a viable option for increase the use of biomass efficiently in the Brazilian energy sector; but little is known about this. This work aims to assess the energy potential and the influence when used N₂ and CO₂ atmospheres on biochar from sugarcane bagasse (SCB) produced

Keywords: Sugarcane bagasse. Torrefaction. Biofuel. Biochar. Energy.

1. INTRODUCTION

As the world population increases, there is a significant increase in energy demand, which leads not only to a decrease in fossil fuel reserves but also to serious pollution problems due to significant greenhouse gas emissions (GHG). Many efforts are being directed at the development of renewable energies, particularly biomass energy due to their wide availability worldwide (Codina Gironès et al., 2017; Khoo et al., 2013; Liu and Han, 2015; Shemfe et al., 2015; U.S. Energy Information Administration, 2014).

Currently, biomass combustion is considered the strategy with low economic risk for the generation of energy, encouraging its use within the energy sector (Codina Gironès et al., 2017; da Silva et al., 2017; Liu and Han, 2015) and also has the potential to assist several governments to provide energy through renewable sources (IRENA, 2015; Khoo et al., 2013). However, untreated (e.g. in nature) biomass is not an ideal energy loader and its direct use in conventional combustion systems faces major challenges, from its inherent properties to the design of new combustion chambers (Liu and Han, 2015).

To improve the energetic content of biomass, recent studies suggest that the torrefaction process could be used, as it has a great potential for industrial use and increases the yield of biochar production. Studies by Chen et al. (Chen et al., 2015), Da Silva et al. (2017), Conag et al. (2018a, 2018b), Cha et al. (2016) and Puente et al. (2017) suggest that the biochar produced by torrefaction is not only cheap and environmentally friendly but also, it is the only biofuel that could be burned directly in conventional combustion systems. Already studies by Conag et al. (2018) suggest that biochar could conserve or improve the combustion efficiency of coal in the generation of heat and energy when compared to in nature biomass.

Although the elemental composition of the biochar is carbon (C), hydrogen (H), oxygen (O), ash, traces of nitrogen (N) and sulfur (S), it varies according to the type of biomass from which biochar was produced, as well as the torrefaction conditions. According to Liu and Han (2015), although there is much work on the production of biomass

torrefied and biochar. most studies are directed to use in soil remediation or GHG reduction as adsorbent. Consequently, limited studies are available on the use of biomass torrefied and biochar in the energy sector and they have simple thermal characterizations for kinetic studies. However, there is a lack of technical information on the quality of the biomass torrefied and biochars produced to be used as alternative biofuels in conventional combustion systems. This lack of knowledge can lead to the production of biomass torrefied and biochar not suitable for burning and leading to problems related to the production of slag and scale in the combustion chambers. Recent studies by Conag et al. (2018b) indicate that there are currently no specific standards to evaluate the quality of biochar as an alternative biofuel; however, standards related to solid fossil fuels could be adopted.

In Brazil, the demand for biomasses exclusive to the energy sector (e.g. sugarcane, sweet and biomass sorghums) favored research on the production of first and second generations biofuels, as well as, in cogeneration. However, it was observed significant quantities of residues generated by sweet sorghum and biomass sorghum are as large as that produced by sugarcane, presenting the same problems in their final disposal. Recently, Da Silva et al. (2017) pointed out that Brazil could become the main producer of torrefied biomass in the world due to its climatic conditions. In this situation, the study of value added to the application of biomass torrefied as biofuel in the energy sector can provide some advantages and is a viable option to increase the use of biomass efficiently in the Brazilian energy sector (da Silva et al., 2017).

This work aims to evaluate the production of biomass torrefied using two kind of atmosphere, i.e. nitrogen (N₂) and carbon dioxide (CO₂) and the energy potential of biomass torrefied produced as alternative biofuel. This will bring technical information relevant to future studies on the use of biomass in combustion and oxy-combustion processes.

2. MATERIALS AND METHODS

2.1 Materials

In this study the most important bagasse for the Brazilian energy sector will be used, e.g. sugarcane bagasse (SCB) (Fig. 1a). Sample of biomass was prepared to torrefaction tests (i.e. grinding, milling and sifting). The average particle size obtained to biomass characterization and torrefaction test was 463 μm (Fig1b).



Figure 1. Brazilian lignocellulosic biomass: (a) sugarcane bagasse *in natura*. (b) sugarcane with 463 μm .

2.2 Experimental Test

In each torrefaction test, the prepared biomass will be weighed and placed in the alumina crucible around 1 g., which will be inserted into the tubular reactor (Fig. 2). so an purge gas at a flow rate of 100 mL/min will be injected into the reactor, and only after 10 min of gas injection, the reactor will be turned on. The reactor will be heated from room temperature to process temperature (e.g. 300 °C) at a heating rate of 10 °C/min and a residence time (or isotherm) of 45 min. These tests should be done using the two kind of gasses, i.e. N₂ and CO₂. All the biochars produced were characterized to determine the energy potential and quality of biochar as alternative solid biofuel.



Figure 2. Tubular Reactor RTV of FORTLAB 1200/IZ used to torrefaction test

2.3 Energy potencial

The biochar produced will be characterized by proximate analysis and calorimeter analysis. The proximate analysis was used to obtain the content (%) of moisture (M), volatile material (VM), carbon fixed (CF) and ash (A) for each biochar. The calorimeter analysis was used to obtain the high heating value (HHV). Using these variables, we can to determine VM, CF, A and HHV in dry base (Eq. 1 – 4).

$$\%FC_{db} = FC \times \left(\frac{1}{100 - M} \right) \times 100 \quad (1)$$

$$\%VM_{db} = VM \times \left(\frac{1}{100 - M} \right) \times 100 \quad (2)$$

$$\%A_{db} = A \times \left(\frac{1}{100 - M} \right) \times 100 \quad (3)$$

$$\%HHV_{db} = HHV \times \left(\frac{1}{100 - M} \right) \times 100 \quad (4)$$

The results of the proximate and calorimeter analysis provide data of fixed carbon (% FC_{db}), volatile material (% VM_{db}), ash content (% A_{db}) and calorific power surpluses (% HHV_{db}). Then the energy potential of the biomass torrefied will be calculated using Eq. (5) through (9).

$$FR = \frac{FC_{db}}{VM_{db}} \quad (5)$$

$$VI(MJ/kg) = \left(\frac{HHV_{db} - 0.338FC_{db}}{VM_{db} - M} \right) \times 100 \quad (6)$$

$$Y_M = \frac{W_T}{W_i} \quad (7)$$

$$R_{DE} = \frac{HHV_{BT}}{HHV_{Biomass}} \quad (8)$$

$$Y_E = Y_M(R_{DE}) \quad (9)$$

The FR is the fixed carbon to volatile material ratio, VI is the heat capacity of volatile material from biomass torrefied, R_{DE} is a energy density ratio, Y_E is a energy yield of the torrefaction process. According to Conag et al. (2018) the FR (fixed carbon ratio for volatile material) and VI (volatility of flammability) are named combustion indexes that allow to evaluate the quality of the biochar. The FR ratio values are between 0.5 and 3. VI should be > 14 MJ/kg, it should be noted that these indexes are used in the evaluation of solid fossil fuels in thermoelectric plants.

3. RESULTS

3.1 Torrefaction test

After to realize the torrefaction tests, the sugarcane bagasse (SCB) and all SCB torrefied samples were characterized using proximate and calorimetry analysis. That results are shown on the Tab. 1. We can see the SCB had a high content of volatile material (VM) and low content of fixed carbon (FC) with approximately 74,17 % and 16,64 % respectively. This SCB characteristics provides a heat capacity of 17,38 MJ/kg which it is a normal feature of biomass *in nature*.

When observed the results of VM content from SCB torrefied on the Table 1, we can see the all torrefied samples on CO_2 atmosphere had lower VM content in their structure when compared with all torrefied samples on N_2 atmosphere. This indicates that samples of SCB torrefied on CO_2 atmosphere had a major mass loss when compares

with samples of SCB torrefied on N₂ atmosphere. Consequently, it can be said that CO₂ atmosphere promoted a major volatility elimination from SCB structure in the torrefaction process.

When the torrefaction process was realized on 300 °C of temperature and 30 min of isothermal time, the difference of VM and FC content between CO₂ and N₂ atmospheres from the SCB torrefied samples, were highest ($\Delta VM = 10.24$ $\Delta FC = 11.36$) that when compared with difference of VM and FC content between CO₂ and N₂ atmospheres from torrefied samples produced on 250 °C ($\Delta VM = 3.42$ $\Delta FC = 1.46$) and 350 °C ($\Delta VM = 2.69$ $\Delta FC = 0.08$).

On Table 1 can be observed when the temperature is increased on the torrefaction process, the heat capacity of SCB torrefied samples are increased too. Must be noted the HHV higher increase is when torrefaction process used CO₂ atmosphere, though the results the SCB torrefied yield (Y_M) are similar on both atmosphere (Tab. 1).

Although these results are interesting. The biomasses torrefied should be evaluated to determine their energy quality to be used in combustion processes in thermoelectric plants.

Table 1. Yield of biochar, proximate and calorimetry analysis for SCB in nature and SCB torrefied

Biomass	T _P (°C)	t _R (min)	Atmosphere	Y _M (%)	VM _{db} (%)	FC _{db} (%)	A _{db} (%)	HHV _D (MJ/kg)
Sugarcane bagasse SCB	<i>In nature</i>			---	74.17	16.64	5.27	17.38
	250	30	CO ₂	82.61	69.17	25.33	5.49	18.69
		30	N ₂	82.00	72.59	23.87	3.54	18.33
	300	30	CO ₂	54.44	52.62	43.42	3.97	25.51
		30	N ₂	52.00	62.86	32.06	5.08	20.69
	350	30	CO ₂	42.50	37.22	56.29	6.49	33.17
		30	N ₂	41.00	39.91	56.37	3.72	28.22

3.2 Energy potential of biochar produced

The SCB torrefied samples were analyzed, in order to determine the energy potential to be used as alternative solid fuels. For that, the combustion indexes, such as: FR, VI, R_{DE} and Y_E were determined. The results are shown on the Tab. 2 and Fig. 3. On Table 2 and Figure 3a can be seen that FR index for SCB torrefied samples enhances with increasing temperatures, being higher for the SCB torrefied samples at 350 °C when both atmospheres were used. Must be mentioned when used 300 °C of torrefaction temperature, the FR ratio of SCB torrefied sample on CO₂ atmosphere is 39 % higher than SCB torrefied sample on N₂ atmosphere. A low value of FR suggests that the solid would ignite rapidly due to the high volatile content (VM). However, a high content of the volatile material in the biomass can result in incomplete combustion due to the speed and difficulty in controlling the combustion. According to Conag et al. (2018a), the FR ratio for solid fuels should be between 0.5 - 3.0, however values above 2.0 may have ignition problems and flame stability. So, the torrefied samples with FR ratio more suitable for good combustion are those produced on 300 °C - 350 °C and CO₂ atmosphere, as well as, 350 °C and N₂ atmosphere.

VI index represents the heat capacity of volatiles material from SCB torrefied samples. According Conag et al. (2018b) the VI index must be above 14 MJ/kg for a good initial combustion, so, can be observed on Tab. 2 torrefied samples produced on 300 °C - 350 °C using both atmospheres are suitable. On Fig. 3b can be seen that torrefied samples on CO₂ atmosphere had VI index values higher than torrefied samples on N₂ atmosphere, principally at 300 °C and 350 °C. Consequently, it can be said the temperature had a larger influence when used CO₂ atmosphere on torrefaction process, due to the heat provides by volatiles material were larger, provably this improved the FR ratio.

In this work, the biomass torrefied with the suitable values of FR and VI indexes (for use in the conventional combustion chambers) were obtained on CO₂ atmosphere. Therefore, it should be pointed out CO₂ atmosphere promotes the volatile elimination on torrefaction process and the biomass torrefied produced will be more suitable for combustion process.

Tab. 2 and Fig. 3c shows the energy density ratio (R_{DE}) from biomasses torrefied at several temperatures. We can observe when used 300 °C and 350 °C of torrefaction temperature, the energy density ratio of SCB torrefied samples on CO₂ atmosphere increased 47 % and 91 %, respectively when were compared with SCB untorrefied. SCB torrefied samples produced at 300 °C and 350 °C on N₂ atmosphere have an energy density ratio increased in 19 % and 62 % respectively when were compared with SCB untorrefied. So, this indicates that the increases of R_{DE} from SCB torrefied samples on CO₂ atmosphere were higher when compares with R_{DE} from SCB torrefied on N₂ atmosphere.

Although the energy density ratio is higher in SCB torrefied using 350 °C (Fig. 3c), the energy yield (Y_E) is similar to SCB torrefied using 300 °C as observed on Fig 3d. These results mean that although on 350 °C were produced a biomasses torrefied with FR, VI e R_{DE} indexes suitable to be used as alternative solid fuel, the energy yield (Y_E) indicates than similar total energy quantity will be obtained when produced SCB torrefied using 300 °C, principally using a CO₂ atmosphere.

Table 2. Combustion Indexes of SCB torrefied.

T (°C)	T (min)	Atmosphere	FR (kg/kg)	VI (MJ/kg)	R _{DE}	Y _E
250	30	CO ₂	0.37	14.16	1.08	0.89
	30	N ₂	0.33	13.86	1.05	0.87
300	30	CO ₂	0.83	19.77	1.47	0.80
	30	N ₂	0.51	15.17	1.19	0.62
350	30	CO ₂	1.51	35.02	1.91	0.81
	30	N ₂	1.41	21.59	1.62	0.67

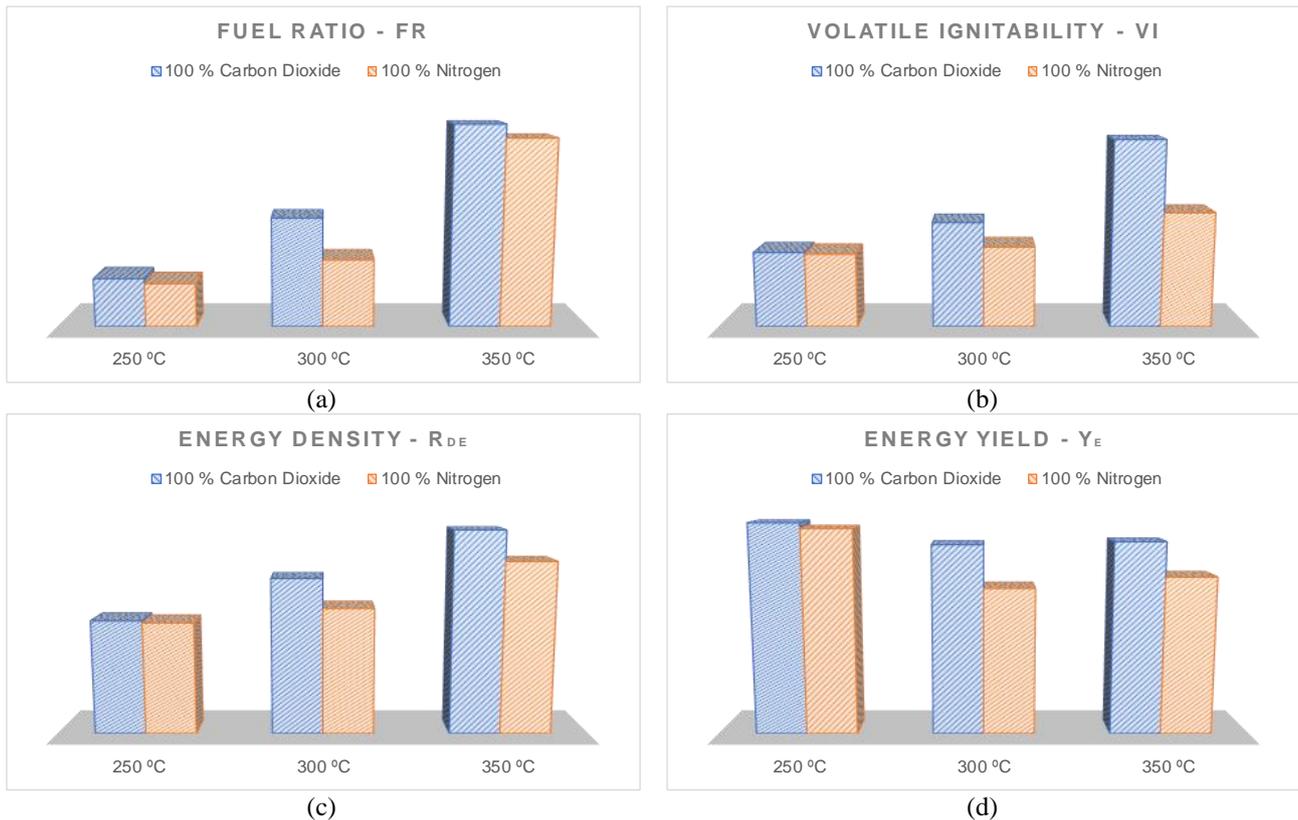


Figure 3. Combustion Indexes and Energy density of SCB torrefied with CO₂ and N₂ atmospheres.

The results above showed indicates that flue gases could be used for produced biomass torrefied, consequently, in this study we realize torrefaction test on an atmosphere with 30 % of CO₂ and 70 % of N₂. The combustion indexes computed are shown on Tab. 3 and Fig. 4.

Table 3. Combustion Index for SCB torrefied on 30 % of Carbon dioxide and 70 % of Nitrogen.

T (°C)	t (min)	Y _M (%)	FR (kg/kg)	VI (MJ/kg)	R _{DE}	Y _E
250 °C	30	82.18	0.34	13.95	1.06	0.87
300 °C	30	52.73	0.60	16.55	1.27	0.67
350 °C	30	41.45	1.44	25.62	1.71	0.71

The Table 3, Fig. 4a and 4b shows that FR ratio and VI indexes suitable, are founded when samples of SCB torrefied are produced with 300 °C (FR = 0.60, VI = 16.55) and 350 °C (FR = 1.44, VI = 25.62). The energy density ratio - R_{DE} of SCB torrefied sample on 300 °C and 350 °C increased 27 % and 71 %, respectively. However, both samples have similar energy yield - Y_E (total energy produced) as showed on Fig 4c. On this situation, when used a flue gas (30 % of carbon dioxide and 70 % nitrogen), the torrefaction temperature suitable would be 350 °C.

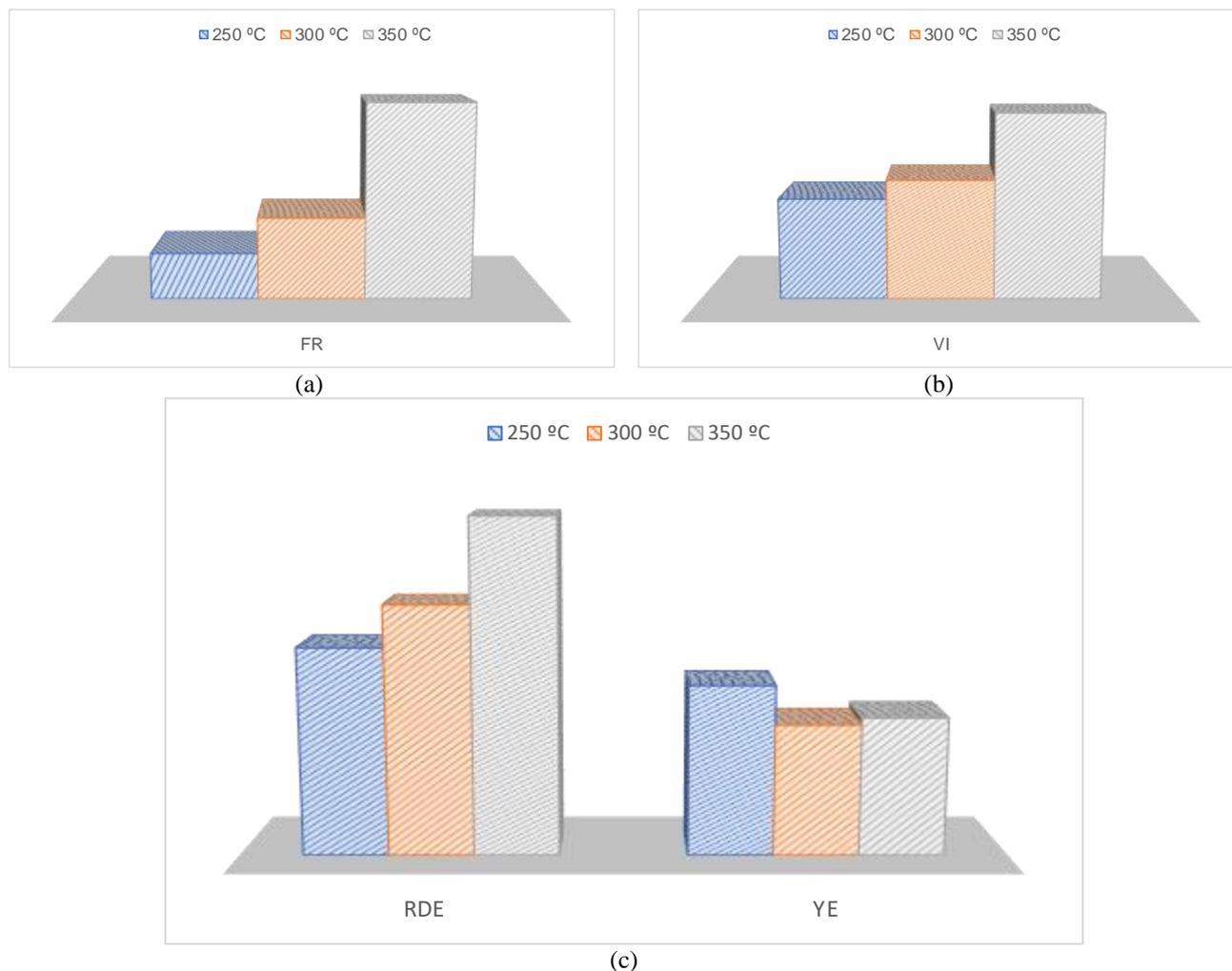


Figure 4. Combustion Indexes from SCB torrefied using 30% of carbon dioxide and 70% of Nitrogen as atmosphere.

4. CONCLUSION

The study of biochar production by torrefaction using N₂ and CO₂ atmospheres indicates that when used CO₂ atmosphere on the torrefaction process, the energy potential of SCB torrefied produced is better than when used N₂ atmosphere. When prepared samples SCB torrefied with 30 % of CO₂, the results of combustion index indicates can be used a flue gas to produce biomass torrefied. The temperature suitable will be around 350 °C.

The N₂ atmosphere is least appropriate for produce biomass torrefied, but when this purge gas is mixture with CO₂ in the torrefaction process, the properties of biomass torrefied are improved.

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