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# TORREFACTION EFFECTS ON PEANUT SHELL COMMERCIAL PELLETS FOR ENERGY USE

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***Abstract.*** *Solid fuels are hampered by their inherent characteristics, such as low density, low energy density, and hygroscopic characteristics. These characteristics could be improved through torrefaction, which is a thermal pre-treatment method to increase energy density and other proprieties. Thus, this work aims to analyze the characteristics of commercial peanut shell pellets, when submitted to torrefaction at various temperatures (200 – 300ºC) and residence times (20, 40 and 60 min), looking for improvements in their quality for use as solid fuel. Therefore, the chemical properties are investigated to determine their characteristics as solid fuel, such as: HHV (High Heating Value); indicators for torrefaction performance; related fuel quality indices (FR, CI and VI). Consequently, when compared with the raw material, torrefied pellets show lower $MC_{wt}$ ~ 4-6%, while, $VM_{db}$ decreases when residence time and process temperature are intensified. Similarly, an increase in $VM_{db}$ and $Ash_{db}$ occurs as volatiles are driven off during that thermal process. Torrefaction itself caused a significant increase in pellets HHV, increasing up to 20 – 22 MJ.kg$^{-1}$, mainly for 300°C process conditions. The solid yields of the samples range between 51–87%, with decreases linearly proportional with the decrease in the energy yield, even with increasing values in HHV´s enhancement factor. The fuel ratio increases from 0.27 in raw conditions, up to values in a range of 0.27-0.79 after the thermal process. A low FR submits that the solid fuel (biomass pellets) would ignite rapidly due to its high $VM_{db}$.*

***Keywords:*** *thermal process, solid fuel, energy properties, combustion indices, fuel improvement.*

## 1. INTRODUCTION

Biomass is characterized by its high moisture content, low HHV (in comparison to liquid and gas fuels), hygroscopic nature and high volume (or low density, kg.m$^{-3}$), thus, low combustion efficiency, as well as, it presents difficulty in collecting, grinding, storing and transporting. In response to the disadvantages encountered in the use of biomass, several pretreatment methods have been studied and developed for their improvement. Among the identified methods, Torrefaction and pelletization are two proposals that stand out in the production of solid fuel (Stelt et al., 2011; Chen et al., 2015).

To upgrade the energetic properties of the biomass, torrefaction is a method that not only can improve the hydrophobicity but also, for example, the combustion characteristics of the torrefied fuel. Nowadays, the most commonly solid fuel in power generation system is the coal, therefore, the combustion systems of this branch were projected to operate based on the ignition and combustion characteristics of the coal. Moreover, considering that biomass is potential a substitute for coal, it would be better if its characteristics were similar to compromise the performance of the combustion system (Conag et al, 2017)

Torrefacation is a modern biomass thermal pre-treatment process that makes it more homogeneous; when combined with pelletization results in a more energy-density product known as torrefied pellet, which has properties similar to Charcoal. Therefore, this type of pellets has great potential in applications where Charcoal is currently used. Also, it improves the competitiveness of biomass in the renewable energy market (Batidzirai et al., 2013, 2014).

Thus, this workaims to analyze the effects of time and temperature of torrefaction on commercial pellets under a controlled atmosphere. Therefore, the chemical properties of pellets produced under various torrefaction conditions were investigated to determine their characteristics as solid fuel, based on proximate analysis, the result of every

torrefaction temperature and duration, correlation of estimation HHV for each sample. Related fuel quality indices (FR, CI and VI) with the parameters of the torrefaction to improve their quality for use as solid fuel.

## 2. METHODOLOGY

The biomass used in the torrefaction process was the commercial peanut shell pellet (Fig.1) at different temperatures and residence times. In this study, five different torrefaction temperatures of 200, 225, 250, 275 and 300 °C, combined with three different residence times of 20, 40 and 60 minutes were chosen as the experimental conditions.



Figure 1. Peanut shell pellets - in natura conditions (as commercialized)

The torrefaction apparatus consists of a precision electronic balance (AD4200) with a capacity of 4200g, precision of 0.01g; porcelain crucibles (Chiarotti, 100 mL capacity), in high refractory porcelain with a lid; and one muffle furnace (Quimis, maximum temperature = 1200ºC), with a temperature sensor type K.

The porcelain crucibles were firstly weighed to determine their empty dry weight and after the crucibles were filled with approximately 20 g of the sample and weighted again. To create a low oxygen environment, the samples were torrefied with the crucible lid. For each temperature, a designated crucible was immediately taken out from the furnace after 20, 40 and 60 min in there. After the torrefaction process, to obtain the biochar properties, proximate and calorific analyses of the raw and torrefied biomass samples were conducted.

### 2.1 Proximate analysis

Proximate analysis was performed according to the technical standards, i.e., NBR 8112 (ABNT, 1986). About 1 g of raw material and 1 g of torrefied sample (weighed to the nearest 0.1 mg) was weighed into a pre-fired and pre-weighed porcelain crucible; its was placed in the muffle furnace oven at 105 °C. The drying procedure was repeated until the decrease in weight of consecutive weighing was 0.0005 g or less. The crucible containing the dried sample allowed cooling before weighing. Moisture content (MC) determination is by Eq. (1).

$$MC_{wb}(\%) = 100[(m_i-m_M)/m_i] \qquad (1)$$

where, $m_i$ $(g)$ is the mass of the sample weighed before drying, $m_M$ is the mass of the sample after drying at 105 °C.

After $MC_{wb}$ determination, the dried samples in the crucibles were further analyzed for their volatile matter content ($VM_{db}$). Covered crucibles containing the samples were placed on the muffle furnace (pre-heated to 900 °C) for 7 min with the furnace door closed. After the designated time, the covered crucibles were taken out and allowed to cool before weighing. Volatile matter content of the sample was calculated using Eq. (2), where $m_{VM}$ is the mass of the sample after the analyzed.

$$VM_{db}(\%) = 100 \ [(m_M-m_{VM})/m_M] \qquad (2)$$

For the determination of ash content ($Ash_{db}$), uncovered crucibles containing the samples after determination of volatile matter content were fired in a muffle furnace heated to 700 °C for 1h and allowed to cool before weighing. The ash content of the sample was then calculated using Eq. (3), where $m_A$ is the mass of the sample after combustion at 700ºC.

$$Ash_{db}(\%) = 100[(m_{VM}-m_A)/m_{VM}] \qquad (3)$$

Also, the fixed carbon content ($FC_{db}$) is determined by difference from the other parameters, Eq. (4).

$$FC_{db}(\%) = 100 - VM_{db} - Ash_{db} \qquad (4)$$

## 2.2 HHV determination

To obtain the high heating value (HHV), correlations based on proximate analysis was used, to provide a rapid, easy and cheap procedure to obtain good estimates of an important parameter. For the raw pellets, a correlation is avalable in in Eq. (5) (Yin, 2010); whereas Eq. (6), is for torrefied pellets (Cordero et al., 2001). Both correlations considered the best error estimation.

$$HHV = 0.2521\ FC + 0.1905VM \qquad (5)$$

$$HHV = 0.1846VM + 0.3525FC \qquad (6)$$

where HHV represents the higher heating value (MJkg$^{-1}$, dry basis), and FC and VM are the fixed carbon and volatile matter contents, respectively, both in weight percent on a dry basis.

Also, for the torrefied pellets, other correlations are available in literature (Soponpongpipat, et al., 2015; Nuchhen and Afzal, 2017), as indicated in Eq. (7) and Eq. (8), respectively; the last one considers the best error estimation.

$$HHV = 35.4879 - 0.3023ASH - 0.1905VM \qquad (7)$$

$$HHV = 0.1846VM + 0.3525FC \qquad (8)$$

The three equations for the torrefied pellets used different samples of biomasses resulting from their thermal treatment in an inert atmosphere at different temperatures. Validationtrough comparison toe experimental results obtained in bomb calorimetric.

## 2.3 Torrefaction performance

To evaluate the torrefaction performance the solid yield, HHV and its enhancement factor and energy yield are important indicators for that. The solid yield evaluate the influence of torrefaction on the mass loss, because when biomasses are torrefied, its dry matter that suffers the thermal degradation (Chen et al, 2015; Zhang et al, 2018). The solid yield is defined as the mass ratio of torrefied and raw mass, presented in Eq. (9)

$$Solid\ yield\ (\%) = (Weight_{\ torrefied}\ /\ Weight_{\ raw})100 \qquad (9)$$

The enhancement is always larger than unity and corresponds as the HHV ratio between torrefied biomass and raw biomass, represented in Eq. (10)

$$Enhancement\ factor = (HHV_{\ torrefied}\ /\ HHV_{\ raw}) \qquad (10)$$

Also, the energy yield defined by Eq. (11), is the energy content in the ratio between torrefied and raw biomass, which is the same to the multiplication of the solid yield and the enhancement factor of HHV,

$$Energy\ yield\ (\%) = (Solid\ yield)\ .\ (Enhancement\ factor) \qquad (11)$$

## 2.4 Combustion indices

Torrefaction performance and solid fuel quality are also evaluated based on the variation of the combustion indices (Conag et al, 2018): fuel ratio (FR), combustibility index (CI), and volatile ignitability (VI), respectively, Eqs. (12), (13) and (14). It should be noted that these indices are used in the evaluation of solid fossil fuels in thermal powerplants.

$$FR = FC_{db}/VM_{db} \qquad (12)$$

$$CI\ (MJ.kg^{-1}) = (HHV_{db}/FR).(115-Ash_{db}).(1/105) \qquad (13)$$

$$VI\ (MJ.kg^{-1}) = [(HHV_{db} - 0.338FC_{db})\ /\ (VM_{db}+M)]\ 100 \qquad (14)$$

The fuel ratio can be obtained from the proximate analysis result and usually typically ranging from 0.5 to 2.0 for used industrially (Ohm et al, 2014). Presence of high volatile matter (VM) content results in low FR and a fuel which is disposed to either emit high amounts of smoke or fuel which rapidly burns, posing a challenge in controlling the ignition flame (Conag et al, 2018).

Combustibility index (CI) is a measure that can be used to estimate the capacity of the material for mixed combustion in coal-fired thermal power plants, and which found to range from 12 to 23 MJ.kg$^{-1}$ for these applications. Moreover, volatile ignitability (VI) is determined to be for most coals used in this type of industry is 14 MJ.kg$^{-1}$, and evaluations the gross calorific value of the total volatiles, in other words the volatile matter and moisture in the solid fuel, considering that fixed carbon (FC) (Conag et al, 2018).

## 3. RESULTS AND DISCUSSION

Table 1 provides proximate analysis and HHV results for pellets in natural conditions (as commercialized).

Table 1. Proximate composition for peanut shell pellets

| | |
|---|---|
| MC $_{wb}$ (%) | 8.43 |
| VM $_{db}$ (%) | 76.88 |
| FC $_{db}$ (%) | 20.47 |
| Ash $_{db}$ (%) | 2.65 |
| HHV (MJ.kg$^{-1}$) | 19.81 |

The impact of torrefaction temperature and residence time on pellets samples weight is demonstrated in Fig 2, where the weight loss has been normalized by the difference of the original sample weight and the final weight after torrefaction. As can be seen in Fig. 2, the residence time of 60 min is the most active to peanut shell pellets torrefaction, regardless of what temperature is. Specifically, almost 50%$_{wt}$ of weight is lost from torrefaction when the temperature is 300°C. Therefore, the thermal degradation of the sample during the process is relatively more violent compared to the other residence times, and this is one of the reasons that the impact of torrefaction on the torrefied samples at this residence time is distinct. Otherwise, it can be observed that in the time residence of 20 min, the weight loss remained linear up to the temperature of 275 °C, and showing that the thermal degradation impact in this parameter of torrefaction is relatively constant.
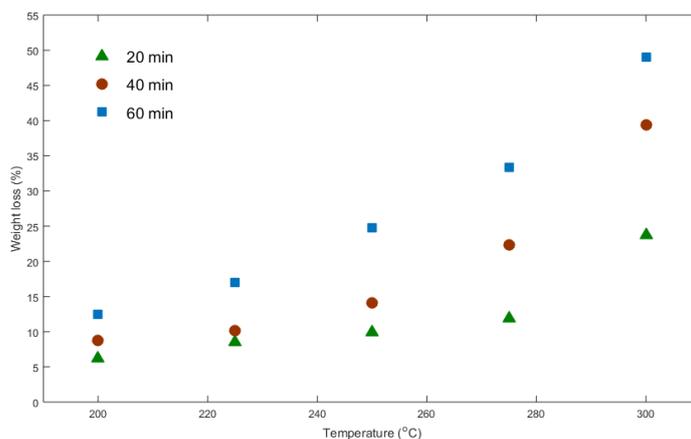


Figure 2. Weight loss distribution as a function of thermal process parameters (residence time and torrefaction temperature).

Pellets became darker with an increasing torrefaction temperature and the pellet surface has lost its shine and smoothness, especially for the pellets torrefied at a higher temperature. Evidence for this visual phenomena, samples becoming darker with the increasing torrefaction temperature, are reported in the literature (Stelt, et al., 2011; Manochehrinejad and Mani, 2018). Also, the pellets retained their shape and almost the integrity after torrefaction, as we can see in the Fig. 3, at time residence of 60 min the integrity of the pellets was the most affected.

Figure 3. Visual conditions for torrified pellets: (torrefaction temperatures (200 to 300°C) and residence times (20, 40 and 60 min).

A summary of the proximate composition of the peanut shell pellets torrefied is showing in Fig. 4 and 5. As the torrefaction temperature increases, the fixed carbon content increased, and the $VM_{db}$ content decreased, approaching the values of raw samples. The moisture content and ash content of the torrefied pellets were considerably lower than that of raw pellets. In general, the moisture content in biomass ranges from 30 to 60 wt%, depending on the type, location, time of harvest and period of storage after harvest (Chen et al, 2015).
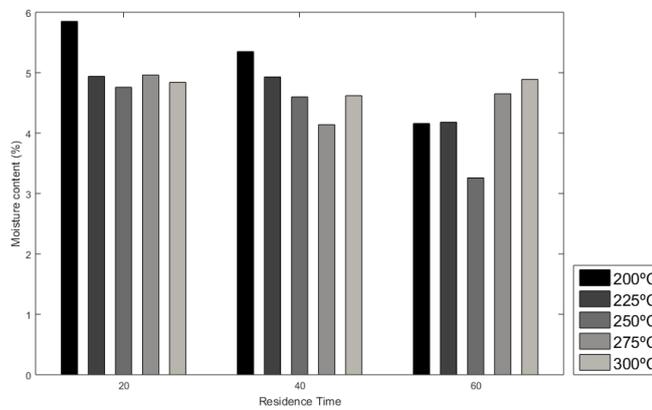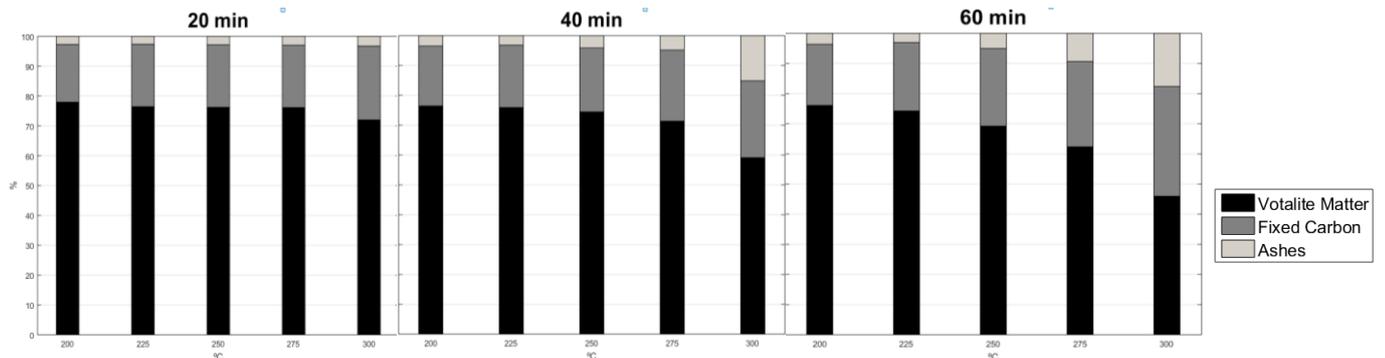


Figure 4. $MC_{wb}$ in torrefied pellets



Figure 5. $VM_{db}$, $FC_{db}$, and $Ash_{db}$ for torrefied pellets

Due to the dehydration process of biomass during torrefaction, light volatiles is released from the materials, with this, the VM content decreases with the increase in time and temperature of the torrefaction process, and these results imply that these wastes possess high reactivity. Similarly, an increase in the fixed carbon and ash happens as volatiles are driven off during the torrefaction. Figure 6 demonstrates the profiles of VM and FC of the samples after torrefaction, which depicts the linear decrease of VM with increasing FC.
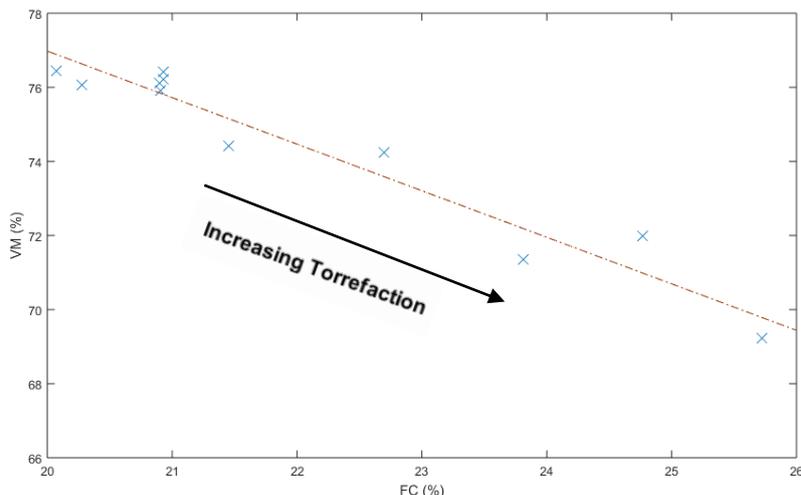


Figure 6. $FC_{db}$ and $VMC_{db}$ behavion on torrefaction process.

Another aspect in the torrefaction is the upgrade the HHV and it is one of the most important properties to characterize the energy content of a substance. The obtained HHV values of torrefied pellets are showing in Fig. 7. Torrefaction itself caused a significant increase of HHV values in the pellets, once undergo torrefaction the HHV of the samples was enlarged to $20 - 22$ $MJkg^{-1}$, especially for the conditions of 300°C.
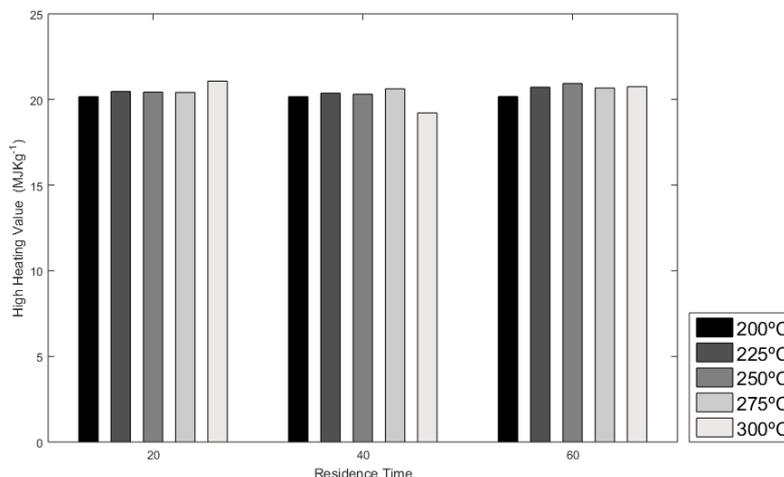


Figure 7. Torrified pellets HHV improvements

The HHV increases with increasing torrefaction temperature and residence time. The correlations suggest that fixed carbon is the main sources of calorific value, who insignificantly which results in the intensification of the HHV of biomass. The HHV for coal are usually in the ranges of $25 - 35$ $MJ.kg^{-1}$(Chen et al, 2015), and the HHV obtained for the pellets samples were in the range of 19.22-21.07 $MJ.kg^{-1}$, which is closer to the HHV of coal, making the pellets became more competitive in the market compared to the HHV.

In Tab. 2 is the results of the HHV for the Eq. (7) and Eq. (8). The second one overestimates the HHV, while the first one underestimates it, when comparing to Fig. 7 results. Future experimental results are to be obtained to the comparison.

Table 2. HHV comparation for torrefied pellets

| | HHV (Eq. 7) | | | | | HHV (Eq. 8) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 200ºC | 225ºC | 250ºC | 275ºC | 300ºC | 200ºC | 225ºC | 250ºC | 275ºC | 300ºC |
| 20 min | 19.82 | 20.13 | 20.11 | 20.09 | 20.79 | 21.21 | 21.49 | 21.45 | 21.42 | 22.02 |
| 40 min | 19.87 | 20.07 | 20.06 | 20.43 | 19.65 | 21.19 | 21.38 | 21.30 | 21.56 | 19.99 |
| 60 min | 19.89 | 20.42 | 20.77 | 20.78 | 21.40 | 21.19 | 21.70 | 21.84 | 21.48 | 21.31 |

The measured solid yields, enhancement factors, and energy yields of the torrefied pellets for the different torrefaction temperatures (i.e., 200, 225, 250, 275, and 300 °C) and time residence (i.e., 20, 40 and 60 min) are listed in Tab 3.

Table 3. Solid yields, enhancement factors, and energy yields for the torrefied pellets

| 20 min | | | | | |
|---|---|---|---|---|---|
| | 200ºC | 225ºC | 250ºC | 275ºC | 300ºC |
| Solid yields (%) | 93.74 | 91.46 | 90.13 | 88.16 | 76.27 |
| Enhancement factors | 1.02 | 1.03 | 1.03 | 1.03 | 1.06 |
| Energy yields (%) | 95.42 | 94.50 | 92.97 | 90.82 | 81.12 |
| 40 min | | | | | |
| | 200ºC | 225ºC | 250ºC | 275ºC | 300ºC |
| Solid yields | 91.27 | 89.90 | 85.91 | 77.68 | 60.57 |
| Enhancement factors | 1.02 | 1.03 | 1.03 | 1.04 | 0.97 |
| Energy yields | 92.93 | 92.45 | 88.09 | 80.87 | 58.78 |
| 60 min | | | | | |
| | 200ºC | 225ºC | 250ºC | 275ºC | 300ºC |
| Solid yields | 87.53 | 83.03 | 75.28 | 66.68 | 50.99 |
| Enhancement factors | 1.02 | 1.05 | 1.06 | 1.04 | 1.05 |
| Energy yields | 89.15 | 86.84 | 79.56 | 69.59 | 53.40 |

The solid yields of the samples range between 76.27–93.74%, 60.57–91.27%, and 50.99–87.53%, in time residence of 20 min, 40 min and 60 min, respectively. The lowest solid yields have been obtained at the most severe torrefaction conditions (i.e., 300 °C and 60 min) with a value of 50.99%. This implies that almost 50% of the pellet was thermally degraded from the torrefaction. Usually, the HHV of biomasses decreased almost linearly with increasing torrefaction mass loss (Chen et al, 2015). Figure 8 shows the decrease in solid yield was linearly proportional with the decrease in the energy yield of the pellet samples, even if the enhancement factor of HHV was enlarged.
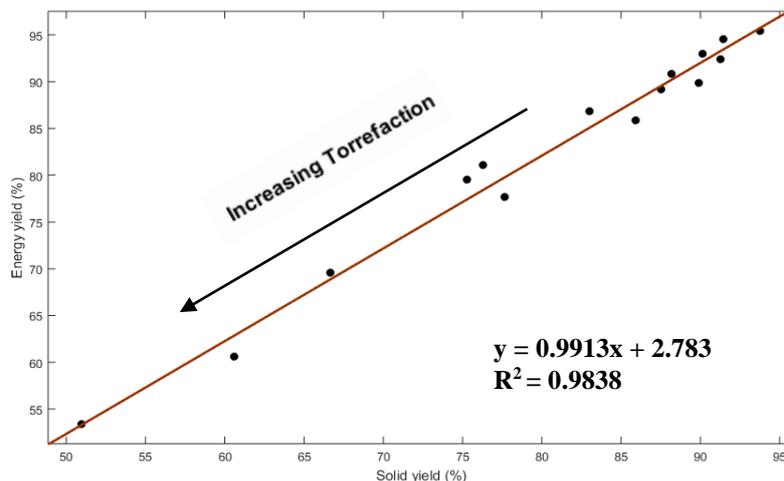


$y = 0.9913x + 2.783$
$R^2 = 0.9838$

Figure 8. Solid and energy yield for the pellets samples

Another form to evaluation or assessment of the torrefaction, and provide a more objective result of the performance and product quality, derived quantities were determined, referred as combustion indices (FR, VI, CI) and they are shown in Tab. 4.

Table 4. Combustion indices for the torrefied pellets

| 20 min | | | | | |
|---|---|---|---|---|---|
| | **200ºC** | **225ºC** | **250ºC** | **275ºC** | **300ºC** |
| FR - Fuel Ratio (FR) | 0.25 | 0.27 | 0.27 | 0.27 | 0.34 |
| CI - Combustibility Index (MJ.kg$^{-1}$) | 86.84 | 79.95 | 79.47 | 79.30 | 65.17 |
| VI - Volatile Ignitability (MJ.kg) | 16.26 | 16.46 | 16.50 | 16.45 | 16.53 |
| **40 min** | | | | | |
| | **200ºC** | **225ºC** | **250ºC** | **275ºC** | **300ºC** |
| FR - Fuel Ratio (FR) | 0.26 | 0.28 | 0.29 | 0.33 | 0.44 |
| CI - Combustibility Index (MJ.kg$^{-1}$) | 81.59 | 78.76 | 74.42 | 64.82 | 41.96 |
| VI - Volatile Ignitability (MJ.kg$^{-1}$) | 16.36 | 16.46 | 16.53 | 16.66 | 16.50 |
| **60 min** | | | | | |
| | **200ºC** | **225ºC** | **250ºC** | **275ºC** | **300ºC** |
| FR - Fuel Ratio (FR) | 0.27 | 0.31 | 0.37 | 0.45 | 0.79 |
| CI - Combustibility Index (MJ.kg$^{-1}$) | 80.23 | 72.23 | 59.01 | 45.80 | 24.28 |
| VI - Volatile Ignitability (MJ.kg$^{-1}$) | 16.61 | 16.64 | 16.89 | 16.58 | 16.60 |

The fuel ratio of the sample increases from 0.27 before torrefaction to values in a range of 0.27-0.79. A low FR submits that the solid fuel (pellet) would ignite rapidly due to the high volatile content (VM). However, even with the biomass has a high content of the volatile material it is possible to result in incomplete combustion due to the speed and difficulty in controlling the combustion. To increase the fuel ratio, it is necessary to increase the torrefaction temperature, reduce the volatile matter, and then increase the fixed carbon (Conag et al, 2018).

The CI was 79.59 MJ.kg$^{-1}$ reduced to within the range 24.28–86.84 MJkg$^{-1}$ after torrefaction. Therefore, this result shows that it seems more appropriate that CI can be maintained if the mixing ratio with coal is optimized.

The Volatile Ignitability (VI) increase from 15.11 MJkg$^{-1}$ to values in a range of 16.26-16.89 MJ.kg$^{-1}$. This indices and its changes could be a useful parameter to indicate the quality of solid fuel. However, due to the influence of moisture content in the torrefied biomass during the storage after torrefaction, these changes in VI could not be an appropriate measure for evaluating a given torrefaction performance.

## 4. CONCLUSIONS

Torrefactions of peanut shell pellet have been performed to assess the improvement of the chemical and thermal proprieties as a commercial solid fuel. From the performances of various torrefaction temperatures (i.e. 200-300 ºC) during 20, 40 and 60 min, useful insights into the pre-treatment of biomass through torrefactions have been obtained. As a whole, the torrefaction with 200ºC in every time residence of the process just released some moisture and light volatiles from the tested sample; it is thus recognized that this procedure had a relatively slight impact in improving the properties of the pellet. In this, the torrefaction with temperature under 250ºC shows the most improvement in the proprieties study. The results of a torrefaction experiment are summarized below:

1.  The optimal torrefaction temperature for each residence time is 300ºC for 20 min, 275ºC for 40 min, 250ªC for 60 min. Compared with the raw pellet, the moisture content and volatile matter of each torrefied material are reduced, but the fixed carbon, ash content, and thus the calorific value are increased.
2.  Of all combinations of torrefaction parameters, the most important was the temperature of 300ºC per 20min, with a moisture content of 4.84%$_{wt,}$ volatile matter of 71.98%$_{db}$, fixed carbon of 24.77%$_{db}$, ashes of 3.25%$_{db}$ and an HHV of 21.07 MJkg$^{-1}$.
3.  The HHV of peanut shell pellets was intensified up to by a factor of 1.26 from torrefaction. Although, the total energy of biomass decreases with increasing torrefaction temperature and residence time, which can be attributed by the fact that the increase in HHV is insufficient to overcome the weight loss.
4.  Combustion indices are a good and important approach when evaluating torrefaction performance as well as the quality of the solid fuel. Therefore, after torrefaction, the fuel ratio is 0.27–0.79, and combustible index (CI) is from 24.28 to 86.84 kJ.kg$^{-1}$. Showing that when the torrefied pellet is combusted with coal, the CI can be maintained by optimizing the mixing ratio with coal.

## 5. ACKNOWLEDGEMENTS

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