Comparative Energy Properties of Torrefied Pellets in Relation to Pine and Elephant Grass Pellets

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Torrefaction is a thermal process that improves the energy properties of plant biomass pellets, providing greater biofuel efficiency for gasification technologies, as well as replacing coal in thermoelectric plants. In Brazil, many agroforestry residues can be improved in value through this technological process, transforming them into modern solid biofuels. There are few studies comparing torrefied wood and elephant grass pellets, especially in relation to their energetic characteristics. This study analyzed the high heat value, energy density, ash content, fixed carbon, volatile materials, lignin, holocellulose, extractives, bulk density, and mechanical durability of these pellets. Due to the absence of Brazilian normative standards for these pellets, the international standard ISO 17225 (2014) was used for comparisons. The results revealed substantial differences among the samples, mainly regarding their moisture content, higher heating value, and energy density in torrefied pellets. It was concluded that these torrefied pellets are biofuels having lower water adsorption, higher heating value, and higher energy density than the pine and elephant grass pellets.

Keywords: Torrefaction; Pelletization; Densification; Bioenergy; ISO 17225

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INTRODUCTION

Plant biomass can be converted into gaseous or liquid fuels by a variety of methods, such as gasification, anaerobic digestion, fermentation, and transesterification. It can also be used as a solid fuel and used in direct combustion for the generation of heat. However, natural biomass has unsuitable characteristics for direct combustion, such as high moisture content (20% to 50%), low heat value, natural hygroscopicity, low bulk density, and heterogeneous forms that result in low conversion efficiency. In addition, it is difficult to grind, store, and transport (Batidzirai *et al*. 2013; Chen *et al*. 2015).

Briquettes and pellets are densified products that have emerged as new forms of solid fuel with higher energy density, which provides savings in transportation and storage facilities and better suitability for use with current technologies (Garcia *et al*. 2016a).

Both mechanical densification (through pelletization) and torrefaction (through heating) are modern technologies of converting plant biomass into a more efficient biofuel, bypassing the weaknesses noted above. Moreover, these processes can be combined; torrefied pellets are an evolution of the solid biofuels (Nunes *et al*. 2014; Peng *et al*. 2015).

The torrefaction (Fig. 1) of biomass raw material followed by pelletizing is the most commonly used thermal pretreatment with pellets (Nunes *et al*. 2014; Chen *et al*. 2015). Torrefaction reduces hemicelluloses and cellulose contents to a lesser extent, so that the plant biomass becomes more fragile and easier to grind (Spîrchez *et al.* 2017). The adsorption of moisture in this torrential biomass is limited (1 to 5%) due to dehydration reactions that eliminate most of the -OH groups, thus limiting the ability to form hydrogen bonds with water (Tumuluru *et al*. 2011; Nunes *et al*. 2014; Peng *et al*. 2015).

Other positive characteristics for the use of torrefied biomass as an energy resource are: higher heating value, lower emission of polluting gases, and greater combustion efficiency (Lunguleasa *et al*. 2015). On the other hand, it is difficult to convert different types of vegetable biomass into a homogeneous final product that meets the quality specifications of ISO 17225-8 (2016). The production process is strongly influenced by the size of the particles, chemical composition, moisture content of the plant biomass, and temperature, which need to be rigorously controlled to obtain quality torrefied products (Spîrchez *et al.* 2017).

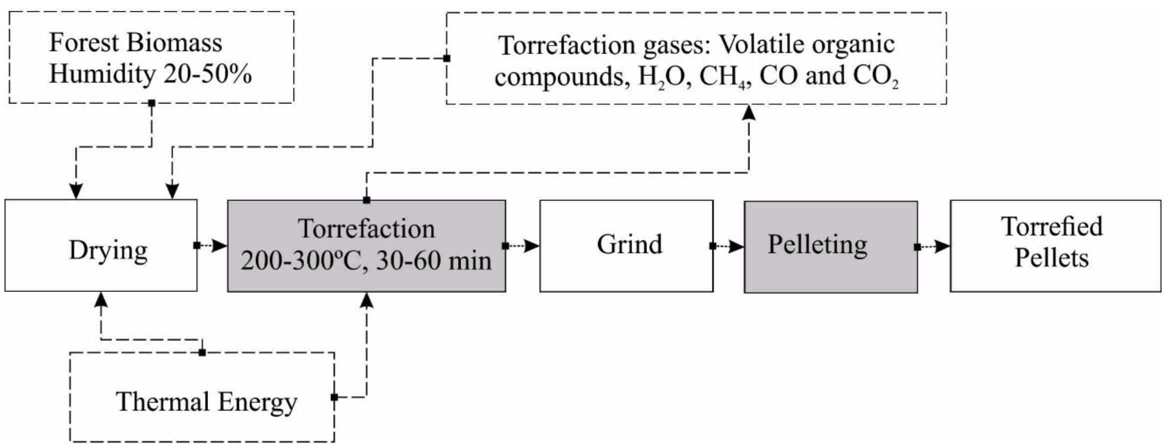

Fig. 1. Scheme of torrefaction and pelletization process for plant biomass

Torrefaction technology may be beneficial to the Brazilian energy sector. Brazil has great potential for expanding production and use of plant biomass as an energy resource because of the large availability of land areas for cultivation and, especially, the intense generation of agroforestry residues.

The diffusion of this technology can bring greater efficiency to the agribusiness of the country because it transforms residue that pollutes the environment if improperly discarded, into a modern resource of energy (Protásio *et al*. 2015; Faria *et al*. 2016; Garcia *et al*. 2016a).

While there are some studies on the pelletizing and torrefaction of plant biomass (Protásio *et al*. 2012, 2013, 2015; Macedo *et al*. 2014), there is a lack of knowledge on the real bioenergetic advantages of torrefied pellets compared with natural ones, especially in Brazil, where this technological process is not applied in industrial scale, as in the United States and Canada. Thus, the objective of this study was to compare the physical, chemical, and bioenergetic properties of torrefied pellets with pine and elephant grass pellets.

EXPERIMENTAL

The analyses were carried out in the period of 2014 to 2016. The original plant biomasses were dried in open air for attaining a moisture content close to 15%, followed by grinding into 2.0 mm size using 40 and 60 mesh sieves. Other characteristics of the raw materials and the method employed for pellet production are described in Table 1.

Table 1. Initial Characterization of Plant Biomass Used in Pellet Production

Pellets	Plant Biomass	Species	Source of the Raw Material	Production Country	Used Technology
P.PIN	Pine pellets	*Pinus* spp (dry sawdust)	Sengés/PR	Brazil	Pelletization industry with 1000 kg.h^{-1} capacity
P.TOR	Torrefied pine pellets	*Pinus* spp (dry sawdust)	Itapeva/SP	Portugal	Torrefied pellets pilot industry with 500 kg.h^{-1} capacity
P.ELE	Elephant grass pellets	*Pennisetum purpureum* (dry sawdust)	João Pessoa/PB	USA	Pelletization laboratory scale with 10 kg.h^{-1} capacity

For the torrefied pellet production, the pine sawdust was dried conventionally and then torrefied with a temperature between 250 ºC and 300 ºC for 30 to 60 min at atmospheric pressure, in the absence of oxygen, and then densified in the form of pellets.

For quantification of high heat value (HHV), IKA C-5000 isothermal calorimeter (Staufen, Germany) was used, and the test was standardized with NBR 8633 (1984). The samples were sieved through 40 to 60 mesh sieves and the fractions retained on the sieve were oven dried at 103 ± 2 °C until a constant mass was obtained. The energy density (ED) of the pellets were calculated by multiplying the high heat value by the bulk density.

Bulk density (BD) was determined using a 5 L volume cylindrical PVC container of height to diameter ratio of 1.37 (228 mm / 167 mm) as required by the standard ISO 17828 (2015). To determine the moisture content of the samples, the greenhouse drying method was used, according to the specifications of NBR 14929 (2003). For the determination of the immediate pellet analysis, the quantification of fixed carbon (FC), volatile material (VM), and ash contents (AC) were performed using the guidelines of norm NBR 8112 (1986). The fixed carbon content was obtained by mass difference.

For the chemical characterization, the pellets were milled in a Wiley-type mill and then sieved through 40 mesh sieve, and the sample retained on the 60 mesh sieve was used. For extractive contents (EC), the TAPPI T-249 (2009) standard was employed, using the total extractive method, using ethanol/toluene (2:1), ethanol, and hot water. The insoluble lignin content was determined by Klason method, and the soluble lignin content was determined by spectrometry from the dilution of the insoluble lignin filtrate. The total lignin content (TLC) was obtained with the sum of these two values, as defined in TAPPI T-222 (2011). The total holocellulose content (THC) was obtained by mass difference.

The number of pellets in 100 g of the material was counted from three samples (each pellet type), as performed by Lehtikangas (2001).

For quantification of the pellets' mechanical strength, by mechanical durability test (DU), approximately 500 g of the product were used and then rotated at 50 rpm for 10 min, according to specifications of ISO 17831-1 (2015). All samples were analyzed in triplicate, except for the mechanical durability, which was repeated five times.

Statistical analysis to estimate the difference between average values (ANOVA) was performed with the support of Excel 2013 software. The 5% probability F-test was performed to determine if the treatments were statistically different, followed by Tukey test.

RESULTS AND DISCUSSION

Figure 2 shows various color shades found in the analyzed biomass pellet samples. In pine pellets, the light color was predominant, because of the characteristic of this softwood, which possessed low basic density and softness.

The elephant grass had a darker color, with small whitish parts indicated that the plant biomass used contained stalk, stems, and leaves. The torrefied pine pellets were dark brown colored, the darkest of the threes examined. This was because of the temperature effect during the torrefaction process.

Fig. 2. Samples of plant biomass pellets used for the tests

ISO 17225-1 (2014) established the length of about 3.15 mm to 40.0 mm as ideal for any pellet application. Some units of the torrefied pellets presented measures below this minimum limit, and the smaller average length of 10.34 mm was obtained. This confirmed the characteristic of higher friability, mentioned by some authors, due to temperature effect and relative increase in lignin content in torrefaction process. It should be noted that this was an undesirable characteristic as the fragile pellets contained larger quantities of fines and hence the risk of transport explosions. However, this friability of torrefied biomass facilitated the grinding step of the raw material, providing energy savings in the pelletization process (Liu *et al*. 2014; Reza *et al*. 2014).

The three pellet samples, P.PIN, P.ELE, and P.TOR, presented average lengths of 14.82, 13.96, and 10.34 mm, respectively. These values were lower than those presented by Toscano *et al*. (2013), which was 17.20 mm. This variation was related to the pelletization technology used and the adjustment of the production process. Thus, P.TOR and P.ELE were not produced on an optimized industrial scale, as seen in Table 1, had smaller lengths than P.PIN, which are commercial products produced with robust industrial pellet equipment. Other process variables interfere with pellet length, such as the compressive strength, temperature, moisture content, particle size and lignin content of the lignocellulosic material (Huang *et al*. 2017).

As for the number of pellets in 100 g, as shown in Table 2, it can be inferred that the pellet brittleness followed the order P.TOR > P.PIN > P.ELE. This quality indicator showed indirectly that the P.ELE had the highest linear length, since there were only 184 pellets in 100 g of the material. Lehtikangas (2001), using pellets of various forest biomasses, found values ranging from 227 to 790. Although the number of P.PIN and P.TOR was in agreement with this, it was noted that the torrefied pellets (P.TOR) were 2.32 and 1.81 times more brittle than P.ELE and P.PIN, respectively.

Table 2. Comparative Characterization among the Three Types of Pellets

Analysis	Torrefied Pellets (P.TOR)	SD	Pine Pellets (P.PIN)	SD	Elephant Grass Pellets (P.ELE)	SD
High Heat Value - HHV (MJ kg^{-1})	22.94a	0.15	20.65b	0.19	18.06c	0.10
Moisture Content - MC (%) db	2.75a	0.18	7.62b	0.09	7.89b	0.04
Volatile Materials - VM (%)	68.00a	0.13	81.71b	0.23	74.88a	4.62
Fixed Carbon - FC (%)	30.47a	0.23	17.97b	0.22	14.61b	4.30
Ash Content – AC (%)	1.52a	0.10	0.32b	0.03	10.51c	0.43
Total Extracts - TE (%)	3.07a	0.17	5.50b	0.43	15.29c	0.20
Total Lignin Content - TLC (%) db	49.79a	1.00	28.94b	0.15	21.64c	0.06
Total Holocellulose Content - THC (%)	40.62a	1.00	65.24b	0.15	52.56c	0.06
Pellets in 100 g	427.00a	10.60	236.00b	6.11	184.00c	3.78
Bulk density - BD (kg m^{-3})	684.14ab	6.77	689.91a	5.16	674.67b	6.76
Mechanical Durability - DU (%)	95.83a	0.20	97.90b	0.08	99.30c	0.06
Energy Density - ED (GJ m^{-3})	15.69a	0.02	14.25b	0.01	12.18c	0.05

Note: Means followed by the same letter, within the same line, do not differ statistically at 5% probability level by Tukey test. SD, standard deviation; db, dry basis

The analysis of variance, through F-test, demonstrated that P.TOR, P.PIN, and P.ELE were significantly different at 5% probability for HHV, AC, TE, TLC, THC, pellets in 100 g, DU, and ED. However, with the standard deviations presented, it was possible to infer that the data, in general, had low variability.

The DU values, which indicates the ability of pellets to sustain destructive forces during transport, values greater than 97.5% are considered optimal by ISO 17225-2 (2014). Thus, it can be inferred that P.TOR pellets exhibited low mechanical resistance. This is a negative factor for biofuel industries because it generates fines in product movements and transport (Kaliyan and Morey 2009).

The BD of the three plant biomass pellets studied revealed higher BD values than the minimum limit established by ISO 17225-1 (2014), which is 600 kg.m^{-3}. For Batidzirai *et al*. (2013), the torrefied pellets also presented BD in a range of 665 to 725 kg.m^{-3}. Thus, all would be in compliance with the international normative ISO standard. However, the BD of P.TOR pellets was lower than that reported by Tumuluru *et al*. (2011) and Rodrigues and Rousset (2009), which was 730 to 850 kg.m^{-3}. These authors pointed out that the initial basic biomass density, changes with temperature and process time as possible reasons for these differences.

The energy density (ED) relates the mass of a biofuel to the energy stored in it. The low values of BD have a negative effect on the ED values of the fuel and, therefore, on its logistic costs (Liu *et al*. 2014; Tumuluru *et al*. 2011). Thus, improving the ED of pellets from 15% to 25% is one of the main objectives of the torrefied process (Batidzirai *et al*.

2013; Chen *et al*. 2015). However, the ED of P.TOR in this study was increased by 10.4% and 28.8% in relation to P.PIN and P.ELE pellets, respectively. Thus the torrefied pellets yielded lower values compared to the pine pellets, and this fact was associated with the higher BD of P.PIN (689.9 kg.m^{-3}) and its variations with the temperature of the production process (Tumurulu *et al*. 2011; Peng *et al*. 2015).

Likewise, the HHV of P.TOR was 27.0% larger than P.ELE pellets and 11.1% larger than P.PIN pellets. In this case, the high HHV of P.TOR was associated with FC (30.5%) and TLC (49.8%) contents presented by this sample, as already reported by other authors (Rodrigues and Rousset 2009; Tumurulu *et al*. 2011).

The moisture content (MC) of P.PIN and P.ELE pellets were in accordance with international normative standards by ISO 17225-6 (2014), which suggested a moisture content below 10%. For P.TOR pellets, the values presented in Table 2 were also convergent with the moisture range in the literature, which is about 1% to 5% (Tumurulu *et al*. 2011; Nunes *et al*. 2014).

Regarding the volatile materials (VM), fixed carbon (FC), and ash content (AC), the data revealed substantial changes after torrefaction. Due to the dehydration process, the moisture and volatile substances were released from the biomass materials, providing a decrease of the biomass VM, while the FC was increased (Tumurulu *et al*. 2011; Chen *et al*. 2015).

These positive changes improved the bioenergy characteristics of the torrefied biomass. In practice, the torrefied pellets which possessed high FC and low VM contents, tend to burn more slowly, *i.e.*, they required a long residence time in the furnace for total burning, when compared to elephant grass pellets (Protásio *et al*. 2012).

The ash content (AC) is a fundamental property that affects the energy characteristics of the biomass. High AC values increase the maintenance costs of burners and contribute to the reduction of heat value, since the mineral elements do not participate in the combustion process (Protásio *et al*. 2012). In addition, the international standards are strict in this regard and only allow AC below 0.7% for residential pellets by ISO 17225-2 (2014). For pine pellets, the AC below 0.50% was obtained in this study (Gil *et al*. 2015; Peng *et al*. 2015; Garcia *et al*. 2016b). Concerning the elephant grass pellets, Paterlini *et al*. (2013) pointed out that the ash percentage at 7.3% level was the main usage limitation for this plant biomass as an energy resource. In this study, P.ELE ash contents were 3.2% higher than those presented in literature and were about 33 times higher than P.PIN. Although P.ELE pellets naturally present high AC values, it was likely that the site of origin and the cropping system employed in the crops influenced the results for this sample.

For P.TOR, the AC value found in this study was in agreement with the range of values found in literature, 0.7% to 2.0% (Peng *et al*. 2015). These torrefied pellets had somewhat higher AC than normal pellets, because of the temperature of the torrefaction process, which caused loss of mass in the plant biomass, while the content of inorganic minerals stayed unchanged (Batidzirai *et al*. 2013).

As for the total extractives (TE), the contents of these low molecular weight components were higher in the case of P.ELE. These promoted the flammability of biomass at lower temperatures due to the higher volatility of these substances (Peng *et al*. 2015). Thus, it was possible to infer that P.ELE were more inflammable than P.PIN and P.TOR samples. These results were consistent with the literature (Reza *et al*. 2014; Peng *et al*. 2015). According to these authors, the TE of the biomass tend to decrease, with the increase of the process temperature, due to the volatilization and degradation of these components. In this study the TE of P.PIN pellets decreased by 2.4% in relation to P.TOR.

In the case of total holocellulose contents (THC), some authors (Poletto *et al*. 2012; Lunguleasa *et al*. 2015) have reported lower values as a result of the degradation of hemicelluloses during torrefaction. The low THC values presented by torrefied pellets, contributed to the increased heat value of the plant biomass.

CONCLUSIONS

1. The energy density of the torrefied pellets was 10.1% and 28.8% higher than pine and elephant grass pellets, respectively.
2. Torrefied pellets resist better to environmental humidity, so they presented low humidity value (2.75%).
3. Torrefied pellets have more ash than *Pinus* (4.75 times) and less than elephant grass (6.91 times).

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