Acta Scientiarum. Technology
ISSN: 1806-2563
eduem@uem.br
Universidade Estadual de Maringá
Brasil

Acta Scientiarum

http://www.uem.br/acta
ISSN printed: 1806-2563
ISSN on-line: 1807-8664
Doi: 10.4025/actascitechnol.v39i4.30198

Sugarcane bagasse pellets: characterization and comparative analysis

Leonardo Ferreira Pedroso de Almeida, Antonio Vanderley Herrero Sola* and Jhon Jairo Ramirez Behainne

*Universidade Tecnológica Federal do Paraná, Avenida Monteiro Lobato, km 04, 84016-210, Ponta Grossa, Paraná, Brazil. *Author for correspondence. E-mail: sola@utfpr.edu.br*

ABSTRACT. This paper presents a study carried out in a Brazilian pellet industry in order to determine the main properties of sugarcane bagasse pellets. Materials and methods are in accordance with standards from the *Associação Brasileira de Normas Técnicas* (ABNT), *Agência de Proteção Ambiental* (EPA) and European Pellets Standard. The pellet properties mean values found in this study are: diameter (9.70 mm), length (22.70 mm), bulk density (726.32 kgm^{-3}), mechanical durability (98.2%), moisture (5.49%), heating value (16.0 MJ kg^{-1}), ash content (8.70%), fixed carbon (14.03%), volatile matter (77.27%), nitrogen (0.28%), sulphur (0.02%) and chlorine (< 0.02 %). The results are compared with those obtained from the literature and discussed according to international standards for biomass pellets, wood pellets and solid biofuel. The comparative analysis showed that there are differences between the results found in our study in comparison with other studies and international standards. The paper also presents the production process energy consumption and cost analysis.

Keywords: pellets, sugarcane bagasse, biomass, bioenergy.

Pellets de bagaço de cana-de-açúcar: caracterização e análise comparativa

RESUMO. Este artigo apresenta um estudo realizado em uma indústria brasileira de pellets, a fim de determinar as principais propriedades de pellets de bagaço de cana. Os materiais e métodos estão em conformidade com as normas da Associação Brasileira de Normas Técnicas (ABNT), Agência de Proteção Ambiental (EPA) e Norma para pellets europeia. Os valores médios das propriedades de pellets encontrados neste estudo são o diâmetro (9,70 mm), o comprimento (22,70 mm), a densidade (726,32 kg m^{-1}), a durabilidade (98,2%), a umidade (5,49%), o poder calorífico (16,0 MJ kg^{-1}), o teor de cinzas (8,70%), o carbono fixo (14,03%), as matérias voláteis (77,27%), o nitrogênio (0,28%), o enxofre (0,02%) e o cloro (< 0,02 %). Os resultados são comparados com outros obtidos a partir da literatura e discutidos de acordo com normas internacionais para pellets da biomassa, pellets de madeira e biocombustível sólido. A análise comparativa mostrou que existem diferenças entre os resultados encontrados em nosso estudo em comparação com outros estudos e normas internacionais. O artigo também apresenta uma análise de consumo e custos com energia no processo produtivo.

Palavras-chave: pellets, bagaço de cana-de-açúcar, biomassa, bioenergia.

Introduction

The use of traditional unprocessed biomass tends to decline in the next decades, while the consumption of bioenergy tends to increase worldwide, regarding the high global primary energy demand (International Energy Agency [IEA], 2012). In this scenario, besides other biofuels, fuel pellets play an important role in the bioenergy market. In addition, the carbon from pellets could be used in many other applications, such as filtering, pharmaceutical and chemical areas (Sousa, Pereira, Silva, & Ferro, 2012).

Nowadays, the main consumers of pellets are Western Europe and North America. The European Union and Japan are projected to be the largest pellets importers in the near future (IEA, 2012). In spite of that some kinds of residues have been employed for thermal energy or electricity generation – such as rice husk studied by Behainne and Martinez (2014) or sugarcane bagasse reported by Hofsetz and Silva (2012) – fuel pellets have some advantages in comparison with unprocessed biomass. Among the advantages is the higher energy density, implying lower storage and transportation costs (Nilsson, Bernesson, & Hansson, 2011).

Sugarcane bagasse pellets have similar characteristics (e.g. NO, CO and SO_2 emissions) and conversion efficiency in comparison to wood pellets (Cardozo, Erlich, Alejo, & Fransson, 2014).

On the other hand, there are some disadvantages. For instance, the high level of ash content at high pyrolysis temperatures could present problems in a gasifier (Erlich, Öhman, Björnbom, & Fransson, 2005). In addition, sugarcane bagasse presents high level of moisture content, demanding higher energy consumption during the drying process.

The main advantage of sugarcane bagasse pellets is the high availability of raw material in Brazil (Hofsetz & Silva, 2012). Sugarcane is produced in many countries and, currently, Brazil is the biggest producer, followed by India, China, Thailand and Pakistan. Brazil produces about 40% of the global production and the top 5 countries together account for 74% of total sugarcane produced (Food and Agriculture Organization of the United Nations [FAO], 2014). The production of sugarcane in Brazil has increased almost 50% in the last decade, reaching 631.8 million tons a year in 2014, with the aim to produce sugar and ethanol (*Empresa de Pesquisa Energética* [EPE], 2015). Each ton of squeezed sugarcane produces around 27% of bagasse. More than fifth percent of sugarcane bagasse is used in the industry sector, and the remaining amount is used in both electricity generation and in the energy sector, for extraction, transformation centers and transportation processes, according to the Brazilian Energy Balance. Despite some initial barriers to be overcome, there is a great potential for enlarging the consumption of solid biomass in the Brazilian domestic market and for exporting, as Walter and Dolzan (2011) pointed out.

Pellets properties from different raw materials, such as softwood (Hartley & Wood, 2008), solid biomass (Wu, Schott, & Lodewijks, 2011), canola (Chico-Santamarta, Chaney, Godwin, White, & Humphries, 2012), bamboo and rice (Liu et al., 2013), wood (Toscano et al., 2013), diverse range of biomasses (Gillespie, Everard, Fagan, & McDonnell, 2013; Cardozo, Erlich, Alejo, & Fransson, 2016), pinewood (Lerna-Arce, Oliver-Villanueva, & Segura-Orenga, 2017), hardwood particles (Nguyen, Cloutier, Stevanovic, & Achim, 2017), lignocellulosic (Stacolino et al., 2017), bamboo, straw and sawdust (Si, Cheng, Zhou, Zhou, & Cen, 2017), different materials (Huang et al., 2017) have been studied by literature. While research on wood and other biomasses pellets is profuse, literature discussing sugarcane bagasse pellets is scarce.

The following studies can be highlighted in the current literature. Erlich et al. (2005) conducted a study to analyze thermochemical characteristics (properties) of sugarcane bagasse pellets from Cuba and Brazil, determining the parameters: shrinkage; mechanical stability; duration of pyrolysis and combustion; char structure and surface area; and char combustion rate. That study showed a significant difference in the properties behavior of sugarcane bagasse obtained from several origins, mainly in terms of ash content, which can cause serious problems in a gasifier. In another study, Erlich et al. (2006) investigated physical effects on both wood pellets and sugarcane bagasse pellets during thermal treatment. The study concluded that pellets properties influence the characteristics of the pyrolysis and gasification processes. Erlich and Fransson (2011) applied some tests in order to analyze the impact of pellets properties on the gasification process. Cardozo et al. (2014) carried out an experimental study aiming to compare the combustion performance of different agricultural residues, including sugarcane bagasse, based on pellets standard in Sweden. Results from that study showed that the physical and chemical properties of the residues influence strongly gas emission levels. In addition, they found that each residue has an impact on the power input, oxygen levels and combustion chamber temperature and that the conversion efficiency depends on the properties and operating conditions during the combustion of the different biomass sources. Wang, Zhuang, Yuan, Yu, and Qui (2015) studied the effect of sugarcane bagasse pellets on enzymatic hydrolysis.

Pellets properties are essentials in the study of performance in thermochemical processes, such as combustion, gasification and pyrolysis. These properties can affect aspects related with transport, storage, handling, fuel conversion and environmental emissions. Pelletizing process of sugarcane bagasse is a great alternative to commercialize such biomass worldwide.

The scope of this paper is to determine the main properties of sugarcane bagasse pellets in order to compare with results from other studies and international standards. Wood pellets standards have been developed in several European countries (ENplus, 2013) and North America (Pellet Fuel Institute [PFI], 2011). Brazil has no standard or guideline for pellets yet. This work also intends to contribute in this direction.

Material and methods

The samples of pellets analyzed in this study were obtained from a pellet factory located in southern Brazil. Currently, this factory produces around 1,200 tons of pellets a month, but there is a plan to increase four times the pellets production in the following years. The raw material comes from industries of sugar and ethanol located near the pellets factory. Regarding the production of sugarcane bagasse pellets, the process is similar to wood pelletizing process (Giacomo & Taglieri, 2009).

In the production process, the raw material comprises only sugarcane bagasse, without addition of any other material. The raw material drying process employs a rotary dryer with 14 m length and 2.5 m diameter, where heat is transferred by convection using air at 350ºC. The dryer has capacity for removing 3,000 kg of water per hour. Induction motors are used at this stage, especially by the following systems: belt conveyor, rotation, convection and ventilation.

In the milling of sugarcane bagasse, a hammer with motor of 60 HP and 3,200 rpm is used in the process. The hammer mill includes a 12 mm opening sieve. A pelletizer with production capacity of 4,000 kg $hour^{-1}$ is used in the final step. The machine is driven by a 300 HP electric motor at 1,190 rpm, pelletizing a matrix of 740 mm outer diameter, 578 mm internal diameter and 2044 holes of 9.54 mm diameter each. Because the temperature of the pellets at the end of the pelletizing process attains approximately 80ºC, pellets are cooled before placed into bags.

The pellets properties analyzed in this work were divided into three categories: 'physical', 'mechanical' and 'chemical'. In the first group the diameter, length, bulk density and moisture were determined. The second category of properties considered the durability and the fines content. Chemical properties included heating value (higher and lower values), volatile matters, fixed carbon, ash content, nitrogen, sulphur and chlorine. For 'physical properties', the standard error was calculated with 95% confidence observing a minimum of 30 elements in the experiments in order to characterize a normal distribution. For other properties, a Student's *t* distribution was applied with the same level of confidence.

The pellet diameter is determined by the pelletizing matrix tool. Considering the expansion suffered after this process or even by tool wear, variations in pellet diameter can occur. For this reason, the experiment conducted a measurement of length and diameter with sampling of 50 pellets using a caliper rule.

The bulk density of raw material was measured using containers. The sample size considered for such measurement was 30 containers with volume of 45.6 m^3 each. The determination of pellets bulk density follows the standard EN 15103:2009 for solid biofuels (European Comitee for Standardization [CEN], 2009a). Measurements were taken by using a cylindrical container with a 5-liter volume (0,005 m^3). The pellets density was determined dividing the mass by the volume. The pellets dimensions were measured with a caliper rule and the mass was obtained by a 0.01 g precision digital balance. A random selection of 50 pellets was taken for the measurements.

Durability is a fundamental characteristic of pellets and depends on the pelletizing time and temperature during the pelletizing process (Lee et al., 2013). This property demonstrates how much pellets resist mechanical impact without being transformed in dust. Fine particles or dust are inconvenient for consumers because they represent health hazard and can affect heating equipment. In this work, the mechanical durability test was carried out in accordance with the standard EN 15210-1 (European Comitee for Standardization [CEN], 2009b).

Moisture content was measured in accordance with the standard NBR 7993 (*Associação Brasileira de Normas Técnicas* [ABNT], 1983). In order to measure the water content in sugar cane bagasse, an infrared analyzer Gehaka (model IV2000) was used, which can determine moisture content in the range from 0 to 100%. For the moisture content measurement of sugarcane bagasse, about 8 g of the substance was placed scattered over the disposable sample pan. A time of 20 min was observed until the end of the measurement procedure. For sugarcane bagasse 50 measurements were taken.

Ash content, volatile matter and fixed carbon were assessed according to the Brazilian standard NBR 8112 (*Associação Brasileira de Normas Técnicas* [ABNT], 1986) for charcoal. For volatile matter determination, a sample of biomass previously dried and weighed was placed in an electric muffle furnace at 900ºC for seven min and then the mass was compared before and after the procedure. In order to determine ash content, a sample of material was placed in an electric muffle furnace at 710ºC until completely burned, and then, the mass was compared before and after the procedure. The fixed carbon percentage was calculated through the difference between 100% and the sum of moisture, volatile matter and ash content. The measurements were replicated three times. The determination of nitrogen, sulphur and chlorine are in accordance with the following standards: EPA 5050 and 4500 NO3 E; EPA 5050 and 4500 SO42- E; EPA 5050 and 4500 Cl G (*Agência de Proteção Ambiental* [EPA], 2014), respectively.

The higher heating value or gross calorific value of pellets was measured in accordance with the Brazilian standard NBR 8633 (*Associação Brasileira de Normas Técnicas* [ABNT], 1984) which prescribes the method for determination of charcoal heating value at constant volume. In order to determine this property, a sample of pellets was crushed and then dried in an oven at 100ºC. After cooled, the calorific value (kcal kg^{-1}) was measured using a bomb calorimeter IKA model C-5000, with reproducibility 0.05 – 0.1 % RSD. The measurements were replicated three times.

In order to determine the consumption and energy costs, an energy analysis per hour was carried out throughout the production process. The power of electric motors was measured with a wattmeter. The drying process thermal energy was obtained from sugarcane bagasse pellets. Energy costs were based on the Brazilian market in 2015.

Results and discussion

The results of the particle size measurements for the sugarcane bagasse, before and after the milling process, are presented in Table 1. The literature has commonly presented pellets length and diameter but has not discussed these characteristics in raw materials, despite their importance in the pelletizing process. Gil, Arauzo, Teruel, and Bartolome (2012) highlighted the milling process importance for particle homogenization. A study carried out by Carone, Pantaleo, and Pellerano (2011) showed that the size of biomass particles is among the most important factors influencing the pellets density and hardness. Stelte et al. (2011) observed that the pelletizing pressure increases with a decreasing particle size of raw material, resulting in higher pellet density. Results of physical and mechanical properties of sugarcane bagasse pellets are presented in Table 2. The main differences between the results found in our work and those found in other studies are analyzed next. It seems to be relevant to observe that bulk density of raw material and fines are among the properties not studied by other authors.

Table 1. Sugarcane bagasse particle size measurements.

	Min. value (mm)	Mean value (mm)	Max. Value (mm)	Standard deviation	Error (±)
Length before milling	3.00	17.70	66.3	11.52	1.15
Length after milling	0.70	5.50	21.40	3.96	0.40
Diameter before milling	0.10	1.10	7.40	1.46	0.15
Diameter after milling	0.10	0.80	2.90	0.62	0.06

Results of physical and mechanical properties of sugarcane bagasse pellets are presented in Table 2. The main differences between the results found in our work and those found in other studies are analyzed next. It seems to be relevant to observe that bulk density of raw material and fines are among the properties not studied by other authors.

Chemical characteristics found in this experiment are presented in Table 3. The Limit of Quantitation (LQ) refers to the concentration of the substance analyzed above, whose results can be obtained with a specific level of confidence. Fixed carbon and volatile matter are among the properties not studied by other authors.

Table 2. Physical and mechanical properties of sugarcane bagasse pellets.

Mechanical properties	Min. value	Mean value	Max. value	Standard deviation	Error (±)
Diameter (mm)	9.60	9.70	10.00	0.10	0.01
Length (mm)	11.00	22.70	33.00	4.94	0.70
Raw material bulk density (kg m^{-3})	192.39	209.55	231.58	10.11	1.85
Pellet bulk density (kg m^{-3})	725.80	726.32	727.00	0.616	---
Bagasse moisture (%)	51.40	53.41	55.60	1.12	0.16
Pellet moisture (%)	5.44	5.49	5.52	0.04	---
Mechanical Durability (%)	97.80	98.20	98.60	0.40	---
Fines (%)	1.40	1.80	2.20	0.40	---

Table 3. Chemical properties based on standards.

ABNT Standards	Mean value	Error (±)
Higher heating value - dry (kcal kg^{-1})	4384	216
Low heating value - dry (kcal kg^{-1})	4063	139
Low heating value (wet) (kcal kg^{-1})	3821	152
Higher heating value - dry (MJ kg^{-1})	18.35	0.90
Low heating value - dry (MJ kg^{-1})	17.01	0.58
Low heating value (wet) (MJ kg^{-1})	16.00	0.64
Ash content (%)	8.70	0.34
Fixed carbon (%)	14.03	0.84
Volatile matter (%)	77.27	2.24
EPA and other Standards	Value	Limit of Quantification (LQ)
Nitrogen (N) %	0.28	0.05
Sulphur (S) %	0.02	0.03
Chlorine (Cl) %	< LQ	0.02

Properties of sugarcane bagasse pellets from other countries have been reported in the literature. In general, pellets properties are very different from the ones in this study. Table 4 presents a comparative study between our study and the work on sugarcane bagasse pellets properties developed by Erlich and Fransson (2011).

The study carried out on sugarcane bagasse pellets produced in Sweden with raw material from Colombia presented different values from our study. In our work both nitrogen and sulphur presented values close to the values reported in that study, but the level of chlorine was lesser than the Limit of Quantification (LQ) and therefore very different from the value presented in that study. As for heating value, our work presents value lesser than the value presented in that study.

Table 4. Comparative analysis with international study.

Sugarcane bagasse pellets properties	Erlich and Fransson (2011)	Our study
Moisture content (%)	9.7	5.49
Bulk density (kg m^{-3})	590	726
Ash content (%)	1.1	8.7
Higher heating value dry (kcal kg^{-1})	4600	4384
Nitrogen (N) %	0.3	0.28
Sulphur (S) %	0.03	0.02
Chlorine (Cl) %	0.05	< 0.02

Figure 1 presents the average of low heating values (wet basis or as received) for sugarcane bagasse pellets found in our work as well as for pellets from diverse feedstock obtained by Telmo and Lousada (2011). Pellets from sugarcane bagasse presented good energy values when compared to other species.

Quality standards are fundamental in order to meet the following requirements: guarantee a common national or international quality of fuel pellets; ensure legal compliance and security among the actors by defining responsibilities and duties; establish limit values and quality indicators, for use, transport and storage; define technical characteristics for heating equipment; inform the final consumers about quality characteristics; ensure customer satisfaction and disseminate biomass fuel, be environmentally friendly. The current state of the art in wood pellet market is focused on certification system, including requirements for pellet production and quality assurance, labelling, logistics and intermediate storage as well as delivery to costumers (ENplus, 2013).

Pellets properties from international standards are presented in Table 5. ISO 17225-2 is a standard for wood pellets (International Organization for Standardization [ISO], 2014a), while ISO 17225-6 is a standard for non-wood pellets (International Organization for Standardization [ISO], 2014b), The European Pellets Standard EN 14961-1 is a general requirement for solid biofuels (European Comitee for Standardization [CEN], 2010). The North American PFI Standard establishes requirements for wood pellets (PFI, 2011).

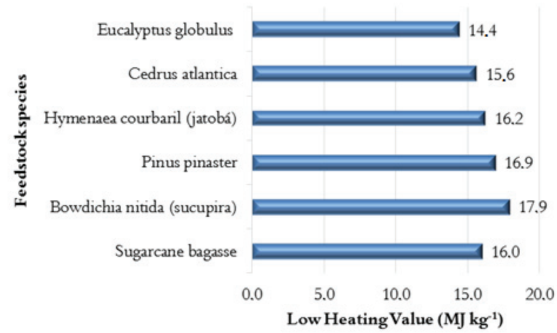

Figure 1. Low Heating Values of pellets from various species.

With regard to physical and mechanical properties, all the norms for pellets (Table 5) establish values for diameter, length, bulk density and durability. The average diameter of sugarcane bagasse pellets found in our work (9.7 mm) is in accordance with ISO 17225-6 for non-wood pellets and EN 14961-1, but it is different if compared with the standard ISO 17225-2 and USA PFI.

The difference between the average value and the maximum value found in our work (±0.3 mm) is below the expected value by the European standard EN14961-1 (±1 mm). The average length (22.70 mm) is in accordance with all the standards that specify this property. The bulk density of pellets found in our work (726.32 kg m^{-3}) is in accordance with all the norms that specify this property. None of the standards analyzed set values for bulk density of raw material. The durability density of pellets found in our work (98.2%) is in accordance with all international standards.

As for chemical characteristics, only moisture content, ash content and chlorine are defined for all the standards. The moisture content found in our work and the heating value are in accordance with all the standards. Ash content found in our work (8.7%) is higher than that found in all standards. The maximum value is verified by ISO 17225-6 (≤ 6.0) and the minimum value (≤ 0.7) is defined by ISO 17225-2. The mean value of fines found in our work (1.8%) is in accordance with ISO 17225-6 and is higher than those found in other standards. Also, the nitrogen, sulphur and chlorine content for sugarcane bagasse pellets found in our work is in accordance with all international standards. Both properties fixed carbon and volatile matters are important parameter of biomass quality, however, they do not appear in the international standards.

Table 5. Pellets properties from international standards.

Specification	ISO 17225-2	ISO 17225-6	EM 14961-1	USA PFI Standard
Diameter (mm)	6,8,12 ± 1	6 - 10	6,8,10 ± 1	5.84-7.25
Length (mm)	3.15-40	3.15-40	3.15-40	≤ 42
Bulk density (kg m^{-3})	≥ 600	≥ 600	≥ 600	608.7-746.9
Durability (%)	≥ 97.5 - ≤ 99	≥ 97.5	≥ 96.5	≥ 95.0
Moisture (%)	≤ 10	≤ 12	≤ 10	≤ 10
Heating value (MJ kg^{-1})	≥ 16.5	≥ 14.5	≥ 16.5	-
Heating value (kcal kg^{-1})	> 3941	> 3463	> 3941	-
Ash content (%)	≤ 0.7	≤ 6	≤ 1.0	≤ 2.0
Fines (%)	≤ 1	≤ 2	≤ 1.0	≤ 1.0
Nitrogen, N (%)	≤ 0.3	≤ 1.5	≤ 0.5%	-
Sulphur, S (%)	≤ 0.04	≤ 0.2	≤ 0.05%	-
Chlorine, Cl (%)	≤ 0.02	≤ 0.1	≤ 0.3%	< 300ppm

During the production process, the electric energy was measured in kWh and transformed to MJ (1 kWh = 3.6 MJ). The thermal energy in the drying process was calculated considering the calorific value of pellets (heating value) 18.35 MJ kg^{-1}. Data is presented in Table 6.

Table 6. Consumption and energy costs.

Type of energy	Energy (MJ)	Cost R$ MJ^{-1}	Price R$
Thermal energy	8808	0.03	264.24
Electric energy	926	0.06	55.56
Material	Mass (kg)	Cost R$ ton^{-1}	Price R$
Sugarcane bagasse	4392	50.00	219.60
Pellets for drying	480	520.00	249.60
Pellets produced	1830	520.00	951.60

The highest cost occurs with the drying process. The energy used to dry the raw material is the necessary energy to reduce the moisture content from 53 to about 11%. As shown in Figure 2, thermal energy is the most consumed in the production process. This result is in accordance with Uasuf and Becker (2011). In our study the energy consumption is 4.81 MJ ton^{-1} of pellets produced with thermal energy and 0.51 MJ ton^{-1} with electricity.

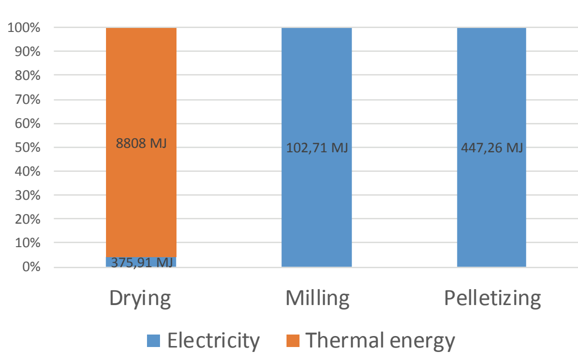

Figure 2. Energy consumption in the process.

Conclusion

The sugarcane bagasse pellets market tends to increase in the future and it needs proper regulation. Therefore, the standardization is an important step to guide producers and consumers. For this purpose, a broad discussion involving all stakeholders seems to be needed in order to establish the parameters for a new standard or guideline.

The results presented in this paper can be applied as a reference to producers, policy makers and researchers. Our study shows that the highest consumption and cost are related to thermal energy. This requires greater attention from pellet producers. Other studies are needed for comparison purposes.

Acknowledgements

We are grateful to both, Brazilian industry of sugarcane bagasse pellets and the Federal University of Technology, Paraná – Brazil (UTFPR) for supporting this research.

References

Agência de Proteção Ambiental. (2014). *Waste's official compendium of analytical and sampling methods – SW 846: test methods for evaluating solid waste, physical/chemical methods*. Washington, DC: United States Environmental Protection Agency.

Associação Brasileira de Normas Técnicas. (1983). *NBR 7993 – Madeira: determinação da umidade por secagem em estufa reduzida a serragem: método de ensaio*. Rio de Janeiro, RJ: ABNT.

Associação Brasileira de Normas Técnicas. (1984). *NBR 8633: Carvão vegetal - Determinação do poder calorífico - Método de ensaio*. Rio de Janeiro, RJ: ABNT.

Associação Brasileira de Normas Técnicas. (1986). *NBR 8112: Carvão vegetal - Análise imediata - Método de ensaio*. Rio de Janeiro, RJ: ABNT.

Behainne, J. J. R., & Martinez, J. D. (2014). Performance analysis of an air-blown pilot fluidized bed gasifier for rice husk. *Energy Sustainable Development, 18*(February), 75-82.

Cardozo, E., Erlich, C., Alejo, L., & Fransson, T. H. (2014). Combustion of agricultural residues: An experimental study for small-scale applications. *Fuel, 115*(January), 778-787.

Cardozo, E., Erlich, C., Alejo, L., & Fransson, T. H. (2016). Comparison of the thermal power availability of different agricultural residues using a residential boiler. *Biomass Conversion and Biorefinery, 6*(February), 435-447.

Carone, M. T., Pantaleo, A., & Pellerano, A. (2011). Influence of process parameters and biomass characteristics on the durability of pellets from the pruning residues of Oleaeuropaea L. *Biomass and Bioenergy, 35*(1), 402-410.

Chico-Santamarta, L., Chaney, K., Godwin, R. J., White, D. R., & Humphries, A. C. (2012). Physical quality changes during the storage of canola (*Brassica napus* L.) straw pellets. *Applied Energy, 95*(7), 220-226.

Empresa de Pesquisa Energética. (2015). *Brazilian energy balance 2015 year 2014*. Rio de Janeiro, RJ: MME/EPE.

ENplus. (2013). *Handbook for the certification of wood pellets for heating purposes (version 2.0)*. Brussels, BE: European Pellet Council.

Erlich, C., & Fransson, T. H. (2011). Downdraft gasification of pellets made of wood, palm-oil residues respective bagasse: Experimental study. *Applied Energy, 88*(3), 899-908.

Erlich, C., Björnbom, E., Bolado, D., & Giner, M. (2006). Pyrolysis and gasification of pellets from sugarcane bagasse and wood. *Fuel, 85*(July-August), 1535-1540.

Erlich, C., Öhman, M., Björnbom, E., & Fransson, T. H. (2005) Thermochemical characteristics of sugarcane bagasse pellets. *Fuel, 84*(March), 569-575.

European Comitee for Standardization. (2009a). *EN 15103:2009 – Solid biofuels. Determination of bulk density. CEN/TS*. London, EN: CEN.

European Comitee for Standardization. (2009b). *EN 15210-1:2009 Methods for determination mechanical durability of pellets. Solid biofuels – fuel specification and classes. CEN/TS*. London, EN: CEN.

European Comitee for Standardization. (2010). *EN 14961:2010 – Solid biofuels — Fuel specifications and classes, Part 1– General requiriments. CEN/TC 335*. London, EN: CEN.

Food and Agriculture Organization of the United Nations. (2014). *Statistics*. Rome, IT: FAO.

Giacomo, G. D., & Taglieri, L. (2009). Renewable energy benefits with conversion of woody residues to pellets. *Energy, 34*(5), 724-731.

Gil, M., Arauzo, I., Teruel, E., & Bartolome, C. (2012). Milling and handling *Cynara cardunculus* L. for use as solid biofuel: Experimental tests. *Biomass and Bioenergy, 41*(6), 145-156.

Gillespie, G. D., Everard, C. D., Fagan, C. C., & McDonnell, K. P. (2013). Prediction of quality parameters of biomass pellets from proximate and ultimate analysis. *Fuel, 111*(September), 771-777.

Hartley, I. D., & Wood, L. J. (2008). Hygroscopic properties of densified softwood pellets. *Biomass and Bioenergy, 32*(1), 90-93.

Hofsetz, K., & Silva, M. A. (2012). Brazilian sugarcane bagasse: Energy and non-energy consumption. *Biomass and Bioenergy, 46*(11), 564-573.

Huang, Y., Finell, M., Larsson, S., Wang, X., Zhang, J., Wei, R., Liu, L. (2017). Biofuel pellets made at low moisture content – Influence of water in the binding mechanism of densified biomass. *Biomass and Bioenergy, 98*(1), 8-14.

International Energy Agency. (2012). *World energy outlook 2012 – renewable energy outlook*. Paris, FR: OECD/IEA.

International Organization for Standardization. (2014a). *ISO 17225-2: Solid biofuels - Fuel specifications and classes Part 2: Graded wood pellets. ISO/TC 238*. Geneva, SW: ISO.

International Organization for Standardization. (2014b). *ISO 17225-6: Solid biofuels - Fuel specifications and classes Part 6: Graded non-woody pellets. ISO/TC 238*. Geneva, SW: ISO.

Lee, S. M., Ahn, B. J., Choi, D. H., Han, G.-S., Jeong, H.-S., Ahn, S. H., & Yang, I. (2013). Effects of densification variables on the durability of wood pellets fabricated with Larixkaempferi C. and *Liriodendron tulipifera* L. sawdust. *Biomass and Bioenergy, 48*(1), 1-9.

Lerna-Arce, V., Oliver-Villanueva, J-V., Segura-Orenga, G. (2017). Influence of raw material composition of Mediterranean pinewood on pellet quality. *Biomass and Bioenergy, 99*(3), 90-96.

Liu, Z., Liu, X., Fei, B., Jiang, Z., Cai, Z., & Yu, Y. (2013). The properties of pellets from mixing bamboo and rice straw. *Renewable Energy, 55*(July), 1-5.

Nguyen, Q. N., Cloutier, A., Stevanovic, T., & Achim, A. (2017). Pressurized hot water treatment of sugar maple and yellow birch wood particles for high quality fuel pellet production. *Biomass and Bioenergy, 98*(2), 206-213.

Nilsson, D., Bernesson, S., & Hansson, P. A. (2011). Pellet production from agricultural raw materials: A systems study. *Biomass and Bioenergy, 35*(1), 679-689.

Pellet Fuel Institute. (2011). *Standard specification for residential/commercial densified fuel*. Seattle, WA: PFI.

Si, T. Cheng, J., Zhou, F., Zhou, J., & Cen, K. (2017). Control of pollutants in the combustion of biomass pellts prepared with coal tar residue as a binder. *Fuel, 208*(November), 439-446.

Sousa, J. C., Pereira, N. C., Silva, M. L. M. C., & Ferro, R. (2012). Production and characterization of water-steam activated carbons made from sugarcane bagasse and molasses pellets. *Acta Scientiarum. Technology, 34*(1), 13-20.

Stacolino, M.V., Cabral Neto, L.F., Protásio, T.P., Carneiro, A.C.O., Andrade, C.R., Guimarães Júnior, J.B., & Mendes, L.M. (2017). Options for generation of sustainable energy: production of pellets based on combinations between Lignocellulosic biomasses. *Waste Biomass Valorization*, 8(July), 1-11. doi: 10.1007/s12649-017-0010-2

Stelte, W., Holm, J. K., Sanadi, A. R., Barsberg, S., Ahrenfeldt, J., & Henriksen, U. B. (2011). Fuel pellets from biomass: The importance of the pelletizing pressure and its dependency on the processing conditions. *Fuel, 90*(November), 3285-3290.

Telmo, C., & Lousada, J. (2011). Heating values of wood pellets from different species. *Biomass and Bioenergy, 35*(7), 2634-2639.

Toscano, G., Riva, G., Pedretti, E. F., Corinaldesi, F., Mengarelli, C., & Duca, D. (2013). Investigation on wood pellet quality and relationship between ash content and the most important chemical elements. *Biomass and Bioenergy, 56*(8), 317-322.

Uasuf, A., & Becker, G. (2011). Wood pellets production costs and energy consumption under different framework conditions in Northeast Argentina. *Biomass and Bioenergy, 35*(3), 1357-1366.

Walter, A., & Dolzan, P. (2011). *Country report: Brazil 2011. IEA bioenergy task 40: sustainable bioenergy trade – securing supply and demand*. Campinas, SP: IEA/Unicamp.

Wang, W., Zhuang, X., Yuan, Z., Yu, Q., & Qui, W. (2015). Investigation of the pellets produced from sugarcane bagasse during liquid hot water pretreatment and their impact on the enzymatic hydrolysis. *Bioresource Technology, 190*(April), 7-12.

Wu, M. R., Schott, D. L., & Lodewijks, G. (2011). Physical properties of solid biomass. *Biomass and Bioenergy, 35*(5), 2093-2105.

Received on December 18, 2015.
Accepted on May 25, 2016.