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HYBRIDIZATION OF ENERGY SOURCES AS AN ENERGY ALTERNATIVE

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Abstract. *The increase in municipal solid waste (MSW) production and its improper disposal creates environmental problems. As a way of dealing with landfill overload and still encompassing the growing demand for energy in cities, new technologies, called Waste-to-Energy (WtE) technologies, which are able to convert waste into energy are gaining more space. Therefore, lignocellulosic residues and MSW have become an attractive energy source for their availability, low price and because they are categorized as a sustainable energy that can substitute fossil fuels. The present work is a case study of the city of Brasília that aims to perform the energy analysis of residues taken from the landfill in Brasília, together with lignocellulosic residues from the pruning of the six most common trees in the Federal District. A synthetic MSW was produced based on the main components of Brasilia's landfill, which are paper, cardboard, plastic and organic residues. All of these components were submitted to a drying and a grinding process. After that, they were mixed in different proportions, based on the gravimetric analysis of the Brasília landfill, to represent the real MSW. The biomass was obtained by a blend of all the six lignocellulosic residues, grounded and mixed. In order to obtain a better fuel, the individual components of biomass species as well as their blend went through the pre-treatment of torrefaction (225, 250 and 275°C) to improve their characteristics such as moisture and fixed carbon content. The obtained solid product was characterized by energy density, calorific value, proximate and ultimate analysis. The final samples consisted of a mixture of different fractions of the municipal solid waste with lignocellulosic residues. The results obtained showed that the torrefied blend sample had an increase of 68.71% in fixed carbon content and 11.10% in HHV, when compared to the raw samples. Regarding the hybrid blend, the one with the highest value of HHV was the torrefied one with the highest proportion of biomass, with an increase of 10.34% in HHV when compared to the raw sample of the same proportion. These results provide a better understanding of this biofuel and new knowledge about whether its use is viable as an energy alternative in the Brasília scenario.*

Keywords: *Torrefaction, biomass, pyrolysis, municipal solid waste, waste-to-energy.*

1. INTRODUCTION

The growing global population and, consequently, the increase in energy demand has led to the drastic reduction of fossil fuel reserves, in addition to environmental problems such as pollution and greenhouse gas emissions (Chen *et al.*, 2015). Thereby, to find alternatives ways to produce energy, more sustainable ways are studied and developed, the so-called Waste-to-energy (WtE).

WtE is a kind of technology used to convert residues into energy using thermochemical conversion processes or biochemical processes (Chen and Kuo, 2010). These technologies have become an attractive alternative to solve the problems related to high energy demand and address other issues such as the large volume of municipal solid waste (MSW) in cities (Vamvuka *et al.*, 2020). Therefore, municipal residues can be used as alternative fuels diversifying the energy matrix, as they present low prices, easy access and large quantities (Vamvuka *et al.*, 2020).

Biomass is an organic material that can be used for energy production. The biomass classification depends on its origin and composition. The biomass can be upgraded as a solid biofuel by the thermochemical conversion process and be applied as an energy alternative to fossil fuels. Biomass is considered a renewable source with a zero emitted carbon balance (Chen *et al.*, 2015).

The biomass conversion product is characterized according to the characteristics of its main components and is also influenced by its origin, moisture, particle size and the thermal process operating conditions (Chen *et al.*, 2015; S. *et al.*, 2020). Biomass composition can be determined by proximate analysis (volatile matter, fixed carbon content and ashes content), calorific analysis and ultimate analysis (Strezov, 2015).

The process of torrefaction (mild pyrolysis) is a thermal process based on the converting the biodegradable organic material into solid fuel (Silveira *et al.*, 2018a, 2020a). This pre-treatment is performed in a temperature range of 200-300°C under an inert atmosphere and aims to produce a solid product with higher heating value or greater energy density (Chen *et al.*, 2015).

The present work investigates the production and energy feasibility analysis of a hybrid biofuel composed of lignocellulosic residues from the pruning of the most common trees in the Federal District and municipal solid waste from the Brasília landfill. The hybridization of these two fuels aims to mitigate environmental issues related to areas degraded by MSW and the energy use of pruning waste.

2. MATERIAL AND METHODS

2.1 Lignocelullosic blend

The lignocellulosic residues used in this work came from urban pruning. The six most common Brasília trees were selected based on data obtained by NOVACAP (Urbanization Company of Brazil's New Capital), this data considered the number of species and call for pruning (Santanna *et al.*, 2020b). The six types of lignocellulosic residues chosen were: *Mangifera indica* (mango tree), *Ficus benjamina* (ficus), *Pelthophorum dubium* (cambuí), *Persea americana* (avocado), *Anadenanthera colubrina* (angico) and *Tapirira guianensis* (pombeiro).

A hammer mill sliced each lignocellulosic sample in order to reduce the particle's size. After that, the samples were sieved (60 mesh) to ensure their homogeneity and, consequently, obtain better thermal processes results. Afterward, the samples were dried in an oven at 104°C until the mass stabilization.

The lignocellulosic blend was made using different proportions of each one of the six samples. The percentage was defined following the representativeness of each tree species in Brasilia (Santanna *et al.*, 2020b). The proximate and calorific analysis from the lignocellulosic samples, in addition to the blend proportions, are in Tab. 1.

Table 1. Proximate and calorific analysis for each species and the lignocellulosic blend (Santanna *et al.*, 2020b).

Species / (%)	Vol.$^{(1)}$	F.C.$^{(2)}$	HHV$^{(3)}$
1. *Mangifera indica* (35%)	72,8	23,2 .	19,2
2. *Ficus benjamina* (20%)	75,8	20,2	18,4
3. *Pelthophorum dubium* (16%)	72,9	21,5	19,4
4. *Persea americana* (16%)	78,7	16,1	19,3
5. *Anadenanthera colubrina* (6%)	71,1	24,5	19,7
6. *Tapirira guianensis* (7%)	72,9	23,9	18,9
Blend (100%)	77,6	17,9	19,3

$^{(1)}$ Volatile matter (%), $^{(2)}$ Fixed carbon (%), $^{(3)}$ High Heating Value (MJ.Kg^{-1}).

2.2 Synthetic municipal solid waste blend

Based on the gravimetric analysis of the Brasilia landfill, obtained by the District Integrated Solid Residues Management Plan (PDGIRS), it was possible to acquire the composition of the real MSW. A synthetic sample of MSW was produced using the three most common materials from the landfill: organic residues, plastic and paper. The proportions for each component were chosen following the actual composition of the MSW. The remaining components, such as glass and metal, were not used since they are inappropriate for thermal processes (Mu'min *et al.*, 2017).

The organic portion was obtained from home composting, a practice in which a set of food leftovers are mixed together with straw and tree remains and go through the fermentation process. The collected material was reserved in a container for 60 days until it was completely decomposed. Home composting was chosen to represent the decomposition that organic materials undergo in landfills. For the paper fraction, it was used magazine paper and cardboard, since it can be seen in Grammelis *et al.* (2009) work that they most resemble the real MSW composition. To simulate the plastic fraction in the real MSW, the PE (polyethylene) was chosen, since this kind of plastic is the most common one (Gerassimidou *et al.*, 2020). Therefore it was used HDPE (high-density polyethylene) from a cleaning product packaging.

The MSW samples were sliced by a hammer mill to decrease the particle size and then sieved (60 mesh). Before the samples were submitted to the experiment,s they were dried in an oven at 104°C until the mass stabilization. The percentage of each component of the MSW blend is on Tab. 2.

Table 2. Synthetic MSW composition.

Material	Description	Percentage
Organic residues	Organic compound from homemade compost	65%
Paper and cardboard	Magazine paper and cardboard	15%
Plastic	HDPE	20%

2.3 Hybrid blend

The hybrid blend was established by producing pellets ($1g$) with two different proportions between synthetic MSW and the lignocellulosic blend, generating four different samples (Tab.3). The proportions were defined based on the work of Hameed *et al.* (2021). The type of lignocellulosic blend was varied to evaluate the influence of torrefaction treatment in the hybrid blend. The samples 1 and 2 used the raw blend, and in samples 3 and 4, the torrefied blend at the temperature of 275°C.

Table 3. Proportions used for the hybrid blend.

Selected proportions		
Components	**Sample 1**	**Sample 2**
Raw lignocellulosic blend	70%	80%
Synthetic MSW	30%	20%
Components	**Sample 3**	**Sample 4**
Torrefied lignocellulosic blend 275°C	70%	80%
Synthetic MSW	30%	20%

Low proportions of MSW was used to minimize the amount of possible pollutants originating from plastic degradation. In addition, the torrefied samples at 275°C was selected due to their better energetic properties (Santanna *et al.*, 2020a,b), allowing a comparison with the raw biomass that exhibits higher moist content and lower fixed carbon content.

2.4 Torrefaction

The lignocellulosic samples and their blend were torrefied aiming to increase the energy density, since the goal of torrefaction is to increase the fixed carbon content by using low heating rates and moderate temperatures, this allows the higher calorific value volatiles to be retained in the product itself. The process was carried out in the Macro-TG Analyser TGA-2000-A. The reactor unit consists of a nitrogen steel cylinder, a gas control rotameter, the TGA-2000A and a computer for system control and data processing (Santanna *et al.*, 2020b). The process was performed under an inert atmosphere with a constant nitrogen (N_2) flow rate of 3.5 $L\cdot$ min^{-1}.

Previously the samples of 2.60 $\pm$ 0,5 mg were dried in an oven from room temperature to 104°C under a heating rate of 20°C.min^{-1}, during 30 minutes until stabilization. After drying, the samples went through the torrefaction process, in which three temperatures were used, 225, 250 and 250°C, a residence time of 60 minutes, at a heating rate of 5°C.min^{-1}. The tests were performed in triplicate, and the mean values and standard deviations were considered.

2.5 Proximate and calorific analysis

The proximate analysis determine the volatile matter, fixed carbon and ashes content, and the calorific was carried out to know the samples' high heating value (HHV). The HHV is the quantity of heat generated by the complete combustion and includes the latent heat stored in the vaporized water, the fixed carbon is the quantity of carbon on the biomass; the more fixed carbon the greater the heating value (Chen *et al.*, 2015).

The raw and torrefied lignocellulosic samples were characterized by proximate (ISO 18123:2015 and 18122:201) and calorific analysis (ISO 1928:2009 and 17225:2014). In addition, the MSW blend and the hybrid blend underwent calorific analysis to characterize the obtained biofuel. All the tests were performed considering the dry basis for the calculation (Santanna *et al.*, 2020a,b).

2.6 Ultimate analysis

Carbon (C) is the primary source of heat released from combustion and hydrogen (H) also determines the heating value and the conversion potential of the biofuel (Chen *et al.*, 2015). However, the presence of hydrogen is associated with low carbon contents, so low hydrogen values are expected. The presence of oxygen (O) is unfavorable because it reduces the heating value of the biomass and favors the formation of CO_2 (Chen *et al.*, 2015). Sulfur (S) is responsible for undesirable reactions during thermal process due to the formation of oxides of sulfur, and it causes severe ash deposition (S. *et al.*, 2020; Wyn *et al.*, 2019).

The ultimate analysis is used to determine the proportions of C, H, N, O and S. The test was performed for raw and torrefied lignocellulosic blends and the synthetic MSW components. It was carried out in a Vario MACRO Cube analyzer with a microanalytical balance following ASTM E777/2008 and E778/2008 standards. The dry basis was considered for calculations of all analyses.

3. RESULTS

3.1 Proximate analysis

The results concerning the proximate analysis and the HHV from the raw and torrefied lignocellulosic blends are on Tab. 4. The results for the torrefied blend at 275°C show higher fixed carbon content and higher HHV. Comparing the raw and the 275°C torrefied lignocellulosic blend results, the volatile matter decreases 17.21%, and the FC increased 68.7%. As seen in the literature, with increasing FC there is a linear decrease of volatile matter during the thermal process (Silveira *et al.*, 2019, 2020b; Galvão *et al.*, 2020). Due to the increase of FC, the high heating value is increased as well, as expected (Silveira *et al.*, 2021a,b,c). There was an increase in HHV of 2.64, 6.67, and 11.10% for 225, 250, and 275 °C treatments, respectively. Regarding the samples thermal degradation after the torrefaction, a solid yield of 93.55% was obtained for the samples at 225°C, 86.34% for the samples at 250°C, and 77.86% for the 275°C samples (Santanna *et al.*, 2020b).

Table 4. Main characteristics of raw and torrified lignocellulosic blends (Santanna *et al.*, 2020a).

Sample	Ashes	Vol.$^{(1)}$	FC$^{(2)}$	HHV$^{(3)}$
Raw	4,49	77,61	17,90	19,32
225°C	4,56	75,56	19,88	19,83
250°C	5,01	70,68	24,31	20,61
275°C	5,55	64,25	30,20	21,47

$^{(1)}$ Volatile matter (%), $^{(2)}$ Fixed Carbon Content (%), $^{(3)}$ High Heating Value ($MJ.Kg^{-1}$).

3.2 Ultimate analysis

Tables 5 and 6 presents the results for the ultimate analysis for the lignocellulosic blend and for the MSW components. The results displayed on Tab. 5 show that the higher the torrefaction process severity, the higher the carbon content and the lower the oxygen content, in line with Lin *et al.* (2019a,b); Silveira *et al.* (2018b). And for the MSW components it can be seen that the plastic has the higher energy potencial since it presents a high carbon content.

Table 5. Ultimate analysis for the lignocellulosic blend (%)

	C	H	N	O	H/C	O/C
Raw	44.91	7.25	0.64	47.84	1.93	0.8
225°C	48.63	6.56	0.76	44.81	1.61	0.69
250°C	50.52	6.31	0.68	43.17	1.49	0.64
275°C	53.3	5.90	0.81	40.80	1.32	0.57

Table 6. Ultimate analysis for the components of the MSW(%)

	C	H	N	O	S	H/C	O/C
Organic	18.01	2.98	1.51	77.33	0.17	1.98	3.22
Cardboard	41.88	6.94	0.26	50.83	0.08	1.98	0.91
Paper	30.68	5.30	0.17	63.82	0.03	2.05	1.56
Plastic	83.07	16.54	0.19	0.05	0.15	2.38	0.0004

3.3 Calorific analysis

Figure 1 shows the results for the calorific analysis for all the blends. The lowest HHV result was for the MSW blend. However when this sample was mixed with the lignocellulosic blend, resulting in the hybrid blend, the value for HHV was higher and, therefore, more heat can be generated.

For the comparison between the samples formed by the raw and torrefied blends, it was possible to see that there was an HHV enhancement of 6.08% between the raw and torrefied 70/30 samples, and the HHV increased 10.34% for the torrefied 80/20 samples.

The torrefied 80/20 blend presents the most advantageous result among the hybrid blends, since smaller fractions of MSW form it. Comparing the HHV results for the MSW blend and the torrefied 80/20 blend, there was a 30.03% increase. However, when comparing with the torrefied blend result, there was a decrease of 4.83%.

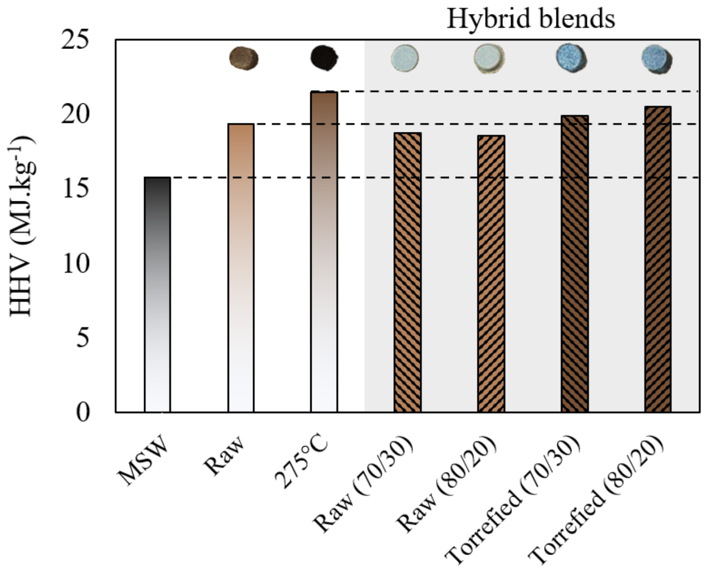

Figure 1. Calorific analysis for the MSW, lignocellulosic and hybrid blends.

4. CONCLUSIONS

The results obtained show that the lignocellulosic residues from Brasília have high energy potential and, when they are combined with MSW, the resulting hybrid blend also presents favorable characteristics. Furthermore, torrefaction pre-treatment was conducted for the lignocellulosic blend showing that treatment temperature is a decisive factor for HHV values and the MSW proportion on the hybrid blend.

For the characterization of the samples, proximate, calorific and ultimate analysis tests were performed. The proximate analysis performed on the lignocellulosic blend aligns with the literature since the blend that underwent the torrefaction process at higher temperatures had more advantageous characteristics in terms of energy. The torrefied blend at 275°C had a higher percentage of fixed carbon and presented an HHV improvement of 11.10% when compared to the raw blend.

The calorific analysis showed that the hybrid blend with better characteristics was the torrefied (80/20), which presents an increase of 10.34% compared to the raw sample with the same proportion. Comparing the HHV results for the MSW blend and the torrefied 80/20 blend, there was a 30.03% increase. However, when comparing with the torrefied lignocellulosic blend results, there was a decrease of 4.83%. These results will be used to guide future works.

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