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A COMPARATIVE STUDY OF WASTE MIXTURES GASIFICATION FOR SYNTHESIS GAS PRODUCTION

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Abstract. *The present work provides a comparison of waste blends utilized as feedstock in a fixed bed gasifier for synthesis gas production. The residues analyzed were polymeric wastes, electric and electronic equipment, wood wastes, residues derived fuel, plastics and rubber, and waste tires. A comparison of the characterization of these residues was performed in terms of their proximate analysis presenting moisture content, volatile matter, fixed carbon, ashes, higher heating value and ultimate analysis regarding the percent of Nitrogen, Carbon, Hydrogen, Sulphur and Oxygen in the raw materials. The gasification and co-gasification of these materials were analyzed in terms of operating parameters such as oxidation and reduction temperatures, feeding rate, air and syngas flows, and tars and chars production. Further, the main comparison parameter analyzed was the Lower Heating Value of the produced gas as well as its composition. The average values of the Lower Heating Value of syngas ranged from 3.0 to 5.4 MJ/m*^{3} *while the chemical composition of the gas had nearly 12% of hydrogen, 20% of carbon monoxide, 3% of methane, 10% of carbon dioxide, and around 55% of nitrogen. The co-gasification of biomasses with materials typically found on municipal solid waste may result in high-quality syngas that can be used for decentralized energy generation.*

Keywords: *waste gasification, synthesis gas, co-gasification.*

1. INTRODUCTION

The global waste generation will increase from 2.01 billion tons in 2016 to around 3.40 billion tons of waste by 2050 according to recent projections. In the Latin America and Caribbean region, a growth of almost 60% is expected, reaching almost 370 million tons of annual waste production in the same period (KAZA et al., 2018). Per capita waste production, which is closely related to income level, is about 1 kg/day in Brazil (ABRELPE, 2019). Figure 1 exposes the average material composition of municipal solid waste around the world and it can be stated that most of the waste is composed by organic materials (44%), followed by paper and cardboard (17%) and plastic (12%).

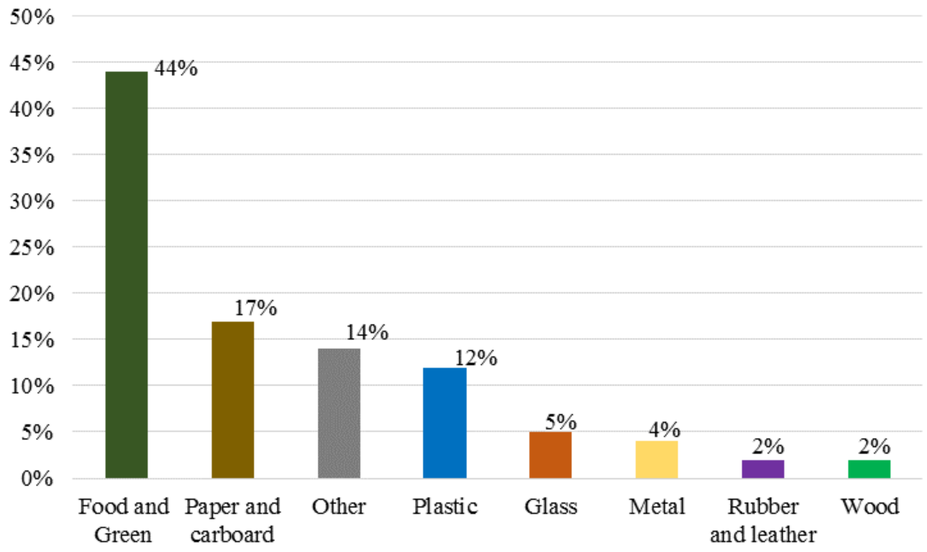

Figure 1. Material composition of waste at a global level (KAZA et al., 2018).

Meanwhile, energy demand has also been on a rise mainly due to population growth and economic development. Concerning the consumer sectors in Brazil, industrial and residential sectors are responsible for the consumption of 37.7% and 25.5% of total electricity generated respectively. The commercial sector accounts for 17% of consumption (EPE, 2018). According to Davis and Gertler (2015), electricity consumption increase in low and middle-income countries is partly due to air conditioning devices use as a consequence of the temperature increase that the planet has been experiencing, as well as to the increase in the per capita income of the population.

A promising solution for the increasing demand for energy and the projections of waste generation increase is the valorization of materials found in collected waste for energy conversion. There are thermochemical processes of waste that can result in useful products such as syngas, biogas, and steam which can be used for electricity generation when associations with internal combustion engines (ICE), gas turbines (GT), and steam turbines are considered (CORONADO; YOSHIOKA; SILVEIRA, 2011)(PEDROSO et al., 2017)(REDDY; ARAVINDHAN; MALLICK, 2016)(CAMPOS et al., 2019). There are mainly three pathways for waste management which include disposal into dumps and landfills, energy recovery techniques such as incineration, gasification, pyrolysis, anaerobic digestion and transesterification, and finally recycling and materials recovery (KABIR; KHAN, 2020).

Technologies such as incineration and anaerobic digestion are the most commonly applied waste-to-energy technologies around the world and have been largely studied over the years (M. A. KARIM AND BRYAN CORAZZINI, 2019)(ROUHOLLAHI et al., 2020). However, the main challenges of waste-to-energy as a dual solution for proper waste disposal and cleaner energy are related to the logistics regarding the collection of waste since materials such as glass and metals are not suitable for energy recovery. The flowchart of Figure 2 exposes the main steps for waste-to-energy starting from the waste generation until the obtaining of biofuels that can be utilized in ICE or GT for electricity generation. Laboratory characterization is important for both the raw materials and for the biofuels produced since it will define their physical and chemical properties.

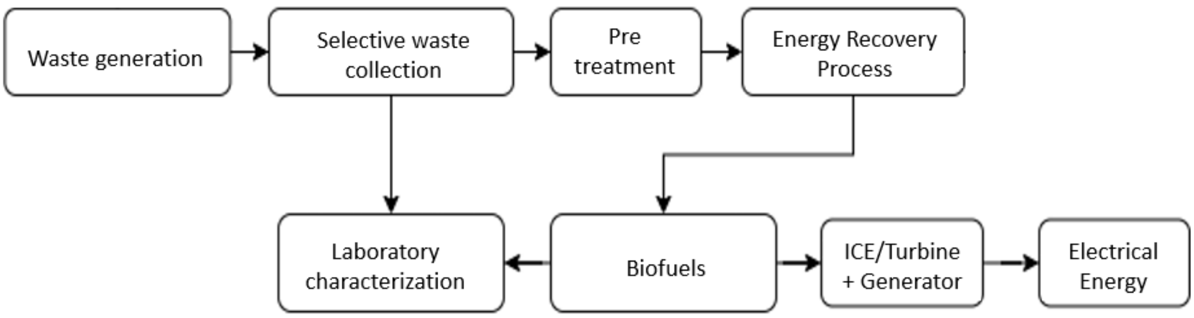

Figure 2. Waste-to-energy flowchart.

Like other energy resources, the use of biomass has limitations in terms of use and applicability, mainly while competing directly with fossil fuels, but it may represent a clean, renewable and efficient energy source (MCKENDRY, 2002). In this sense, biomass utilization for electricity generation has been used as a renewable energy source for reducing the environmental impacts caused by anthropogenic activities. However, recent studies have observed the relation between toxins resulted from incineration plants and the occurrence of certain diseases such cancer and respiratory problems (XU et al., 2019)(TAIT et al., 2020). For this reason, other technologies such as gasification should be more investigated for energy recovery of wastes.

This paper presents a comparison of biomass and waste mixtures utilized as feedstock in a 15 kW gasification unit at the Polytechnique Institute of Portalegre considering previous experiments with materials such as lignocellulosic and polymeric wastes (PANIZIO et al., 2020), waste of electrical and electronic materials (WEEE) (HERMOSO-ORZÁEZ et al., 2020), waste tires and plastic-rubber (CARMO-CALADO et al., 2020), and polymeric waste (PANIZIO; DE BRITO; CALADO, 2019) which are materials commonly found in municipal solid waste. This paper aims to provide a summary of the main results obtained so far in the gasification and co-gasification processes for this is a growing technology that is promising for the valorization of waste materials.

2. METHODOLOGY

The experiments selected for the comparison were performed in a downdraft fixed bed gasifier which is illustrated in Figure 3. The biomass energy recovery unit is composed of two main equipment, a gasification unit (Power Pallets 20 – PP20), and a power generation unit consisted of an internal combustion engine (ICE) associated with a generator. The downdraft fixed bed gasifier is fed with solid residues in the hopper (1), which are dried in a heat exchanger (2). In the Imbert type reactor, the thermochemical process of gasification happens due to the pyrolysis (3), oxidation (4), and reduction (5) zones resulting in the production of the synthesis gas (syngas). Ash and biochar (6) are solid byproducts formed during gasification. For security and monitoring, there is a flare (7) for burning the syngas at the beginning of the process, and in case of an engine stop. Particle separation is performed in a cyclone filter (8) and the produced syngas circulates inside the heat exchanger (2) before being filtered (9) and injected in the ICE (10). The mechanical energy produced is then converted into electricity when the electrical generator (11) is associated with an ICE.

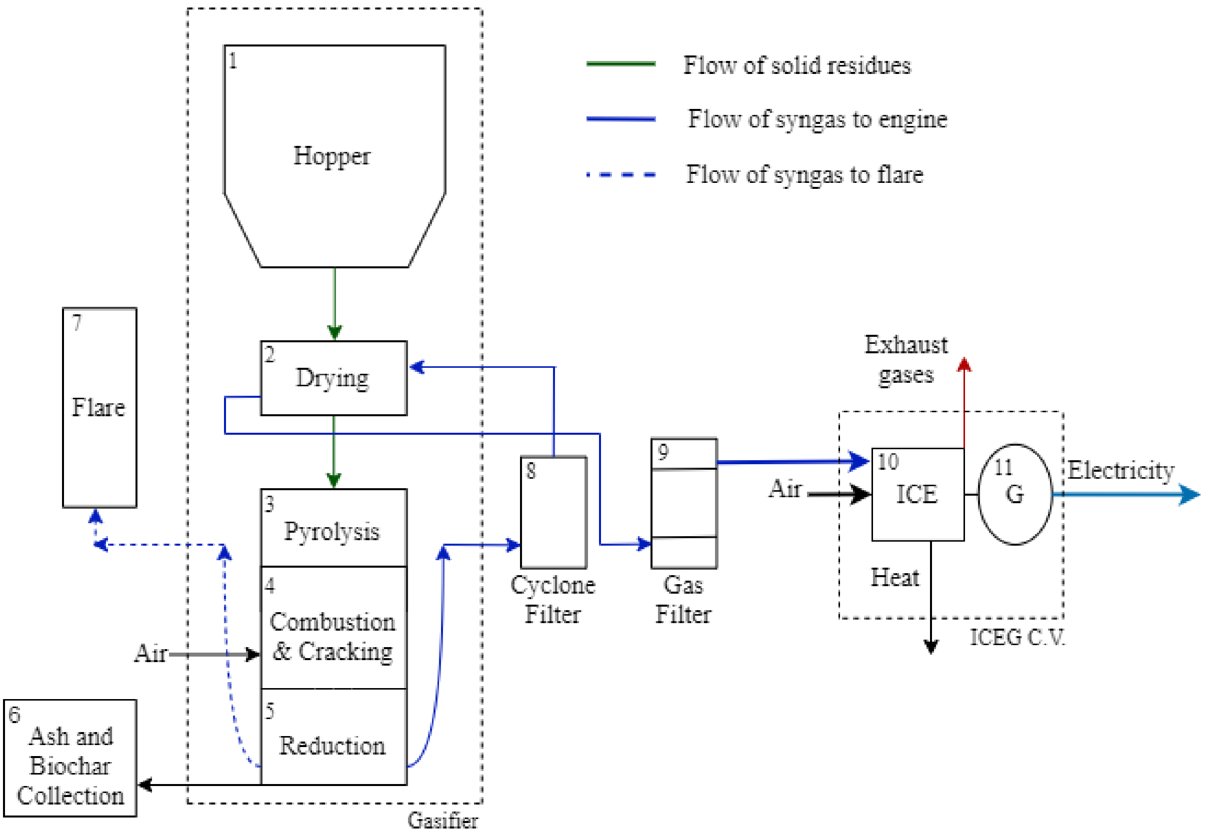

Figure 3. Downdraft fixed bed gasifier with engine association scheme.

Proximate analyses of all waste materials were compared considering the results of their moisture, volatile matter, fixed carbon, and ashes. Meanwhile, the results of the ultimate analysis provided the percent of Nitrogen, Carbon, Hydrogen, Sulphur, and Oxygen as well as the Higher Heating Value (HHV), obtained with a calorimetric analysis.

The feedstock utilized in the experiments consisted of mixtures of waste materials in different blending ratios between them, namely *Eucalyptus* chips (EC) with Refused Derived Fuel (RFD) at 70:30 blending ratio (PANIZIO et al., 2020), olive seeds (OS) with WEEE plastic (WP) at a blending ratio of 90:10 (HERMOSO-ORZÁEZ et al., 2020), *Miscanthus* chips (MC) with plastic & rubber (P&R) (80:20) and with waste tires (WT) (80:20) (CARMO-CALADO et al., 2020), and finally, the results of *Eucalyptus* chips gasification are displayed as a reference since this biomass is widely used as feedstock for energy purposes worldwide.

Furthermore, the results of waste materials blend under different gasification conditions and parameters such as oxidation and reduction temperatures, feeding rate, airflow, syngas flow, and the equivalence ratio are compared. The equivalence ratio (ER) is given by the ratio between real and stoichiometric air flows.

Finally, produced gas quality is performed with chromatography analysis, and the results were compared in terms of the gas composition, that is, the quantities of Hydrogen, Carbon dioxide, Nitrogen, and Methane. Additionally, it was considered as the main comparison parameter the Lower Heating Value (LHV) of the produced syngas.

3. RESULTS AND DISCUSSION

The results of past experiments are compared regarding the characterization of all feedstock materials and the gasification operation parameters of several waste blends regarding the technical conditions of the fixed bed gasifier. Results from proximate analyses showed that polymeric wastes had less than 1% of moisture content, while forest biomass presented about 8%. Meanwhile, the sewage sludge composition is almost totally of moisture content which makes necessary the drying process of this material for energy recovery. Figure 4 exposes the results of proximate analyses of biomass, polymeric, and organic materials on a wet basis.

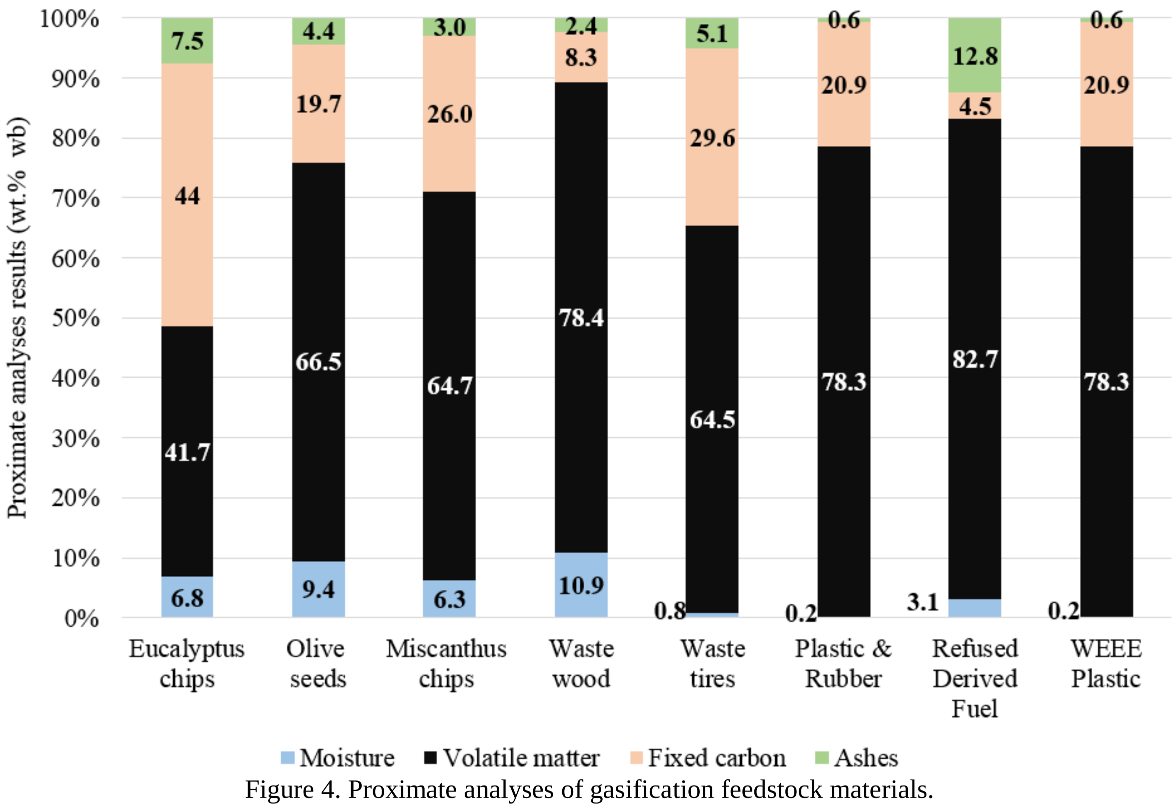

Figure 4. Proximate analyses of gasification feedstock materials.

From ultimate analyses, the carbon content in biomass varieties ranged from about 44% to 55%, meanwhile, some polymeric waste presented very high content of carbon, for instance, the waste tires (75.5%) and WEEE plastic (81.9%), which is associated to the greater values of the Higher Heating Value of those materials as is can be observed from the green line highlighted in Figure 5. However, these last two materials presented greater content of Sulphur compared to forest biomass, further, most of the wood varieties analyzed presented high content of Oxygen and an average of around 7.5% of Hydrogen. WEEE plastic (WP) originated from disposed public luminaries is the material with higher HHV from all wastes compared with a value of 41.8 MJ/kg, while wood biomasses presented an average of around 18 MJ/kg.

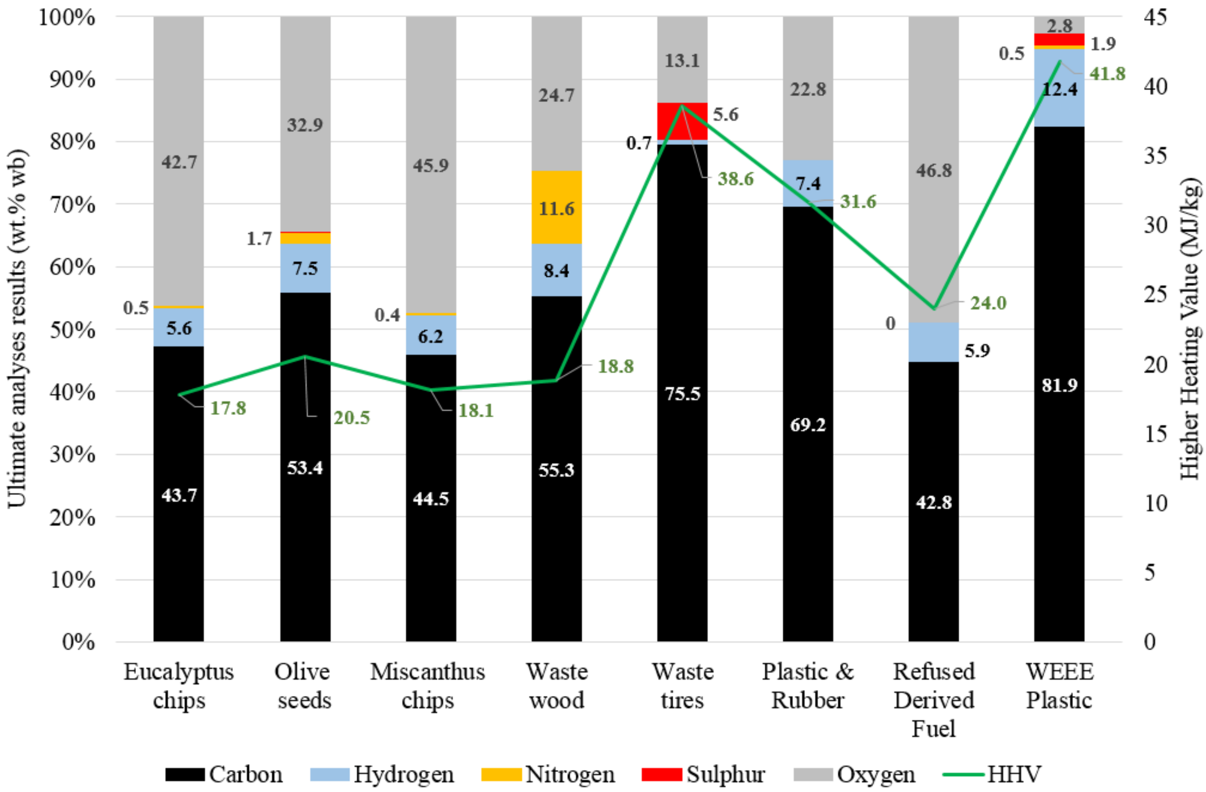

Figure 5. Ultimate analysis and HHV of gasification feedstock materials.

The main operating parameters during the gasification and co-gasification processes are the temperatures of oxidation and reduction zones, feeding rate, air inlet, produced syngas flow, and the production of tars and chars. The equivalence ratio (ER) is usually calculated for determination of gasification efficiency and it is given by the ratio between the real airflow and stoichiometric airflow. All experiments presented ER ranging from 0.25 to around 0.30, which is in accordance with the literature since the ER varies from 0.20 to 0.40 in thermal gasification processes. The reference feedstock was *Eucalyptus* chips, for it is commonly found in the market. It can be observed from Table 1 that the oxidation temperature ranges from 980 K to around 1100 K while the reduction temperature ranges from 770 K to 850 K. The waste blend that showed the highest tars production was from *Miscanthus* with plastic and rubber resulting in approximately 0.36 L/h of tars, while the blending of the same biomass with used tires showed the highest rate of chars' production at around 0.12 kg/h. However, the last waste blend presented a rate of tars production slightly lower than the reference *Eucalyptus*, which among all gasification tests was the feedstock the produced the lowest quantity of such byproducts.

Table 1. Gasification unit operating parameters.

Gasification Feedstock (Blending ratio)	Oxidation temp. (K)	Reduction temp. (K)	Feeding rate (kg/h)	Air inlet (Nm^3/h)	Syngas flow (Nm^3/h)	Tars (L/h)	Chars (kg/h)
Eucalyptus chips	1076	778	6.0	11.1	15.7	0.050	0.096
EC + RDF (70:30)	1063	794	4.1	10.3	14.3	0.135	0.134
Olive seeds + WP (90:10)	981	820	6.9	14.17	19.1	0.128	0.123
Miscanthus + WT (80:20)	1076	808	4.97	9.20	12.89*	0.038	0.231
Miscanthus + P&R (80:20)	1087	844	1.88	9.30	13.04*	0.361	0.040

*Syngas flow calculated according to (ALVES et al., 2019).

The results presented in Table 2 show that the mean values of LHV of produced syngas from co-gasification of waste blends ranged from 3 to 5.4 MJ/m^3. Additionally, the best gas quality was found in the co-gasification of RDF and plastic materials with wood biomasses such as Eucalyptus and Olive seeds. Regarding the composition of syngas, experiments showed an average of 6-12% of H_2, 9-11% of CO_2, 8-20% of CO, 2-4% of CH_4, and 50-60% of N_2.

Table 2. Percentages of main components in produced syngas.

Gasification Feedstock (Blending ratio)	H_2 (%)	CO (%)	CO_2 (%)	CH_4 (%)	N_2 (%)	LHV (MJ/m^3)
Eucalyptus chips	12.9	20	10.7	1.6	55	5.1
EC + RDF (70:30)	12.4	17.8	10.8	3.1	56	5.4
Olive seeds + WP (90:10)	12.7	17.8	9.8	2.7	57	5.42
Miscanthus + WT (80:20)	6.0	10.6	9.7	3.8	55.7	3.64
Miscanthus + P&R (80:20)	5.9	8.3	11.1	3.7	52.5	3.09

From the raw materials' proximate analyses, it can be stated that the ash content is negatively related to the HHV of the material. However, there is a direct proportion between Carbon content and HHV as it can be observed in Figure 5, meanwhile, Oxygen and Nitrogen have a negative effect on energy content. There is also a relation between the volatile content and the production of tars and chars, which is possible to note when comparing Figure 1 with these two parameters from Table 1. Polymeric materials presented high volatile matter content, around 68%, which means that less heat is necessary for the thermochemical reactions if compared to forest biomass, however, the reduced volatile matter of forest biomasses allowed fewer tars production during gasification which is better for power generation through internal combustion engines.

Regarding the quality of produced syngas, there is a clear contribution of H_2 and CO content to the LHV when comparing the results from Table 2, establishing a direct relationship between these two compounds and the Lower Heating Value. Further, air gasification results in high content of N_2 as it is noted in all tests performed, more than 50% of N_2 content, which is in accordance with the literature. Steam gasification can result in syngas with higher LHV compared to air gasification due to increased share of combustibles and reduced dilution of syngas with N_2 (GUNARATHNE et al., 2014).

4. CONCLUSIONS

The gasification process is a promising technology for waste valorization that represents a sustainable alternative for reducing pollutant emissions while allowing energy generation from residues. One challenge of power generation from internal combustion engines fueled with syngas is the presence of tars and chars in the produced gas that can damage such equipment, hence, fuel gas cleaning technologies must be applied for better quality syngas such as adding a scrubber before the ICE syngas inlet.

Co-gasification of biomass with several waste materials resulted in syngas with LHV ranging from 3.0 to 5.4 MJ/m^3 and different compositions, however, they all presented around 12% of H_2, which is a component with high calorific value (about 120 MJ/kg). Besides, syngas produced also had concentrations of carbon monoxide, which has a calorific value of around 10 MJ/kg, and methane, which has a calorific value of nearly 50 MJ/kg. Since the oxidant agent in all experiments was atmospheric air, the concentration of N_2 in the syngas was always about 50% in volume.

It is highlighted that the utilization of locally available biomasses may result in high-quality syngas. For instance, in the case of Portugal, which has a large area of Olive trees plantations, the utilization of Olive seeds blended with plastic waste resulted in a syngas with relatively high LHV if compared to usual feedstocks. The valorization of waste is a sustainable alternative that avoids landfilling while increasing energy generation potential.

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