Environment Protection Engineering

Vol. 46 2020 No. 2

DOI: 10.37190/epe200204

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FEASIBILITY OF USING MUNICIPAL SOLID WASTES REJECTED FRACTIONS AS FUEL IN A BIOMASS POWER PLANT

The viability of partial replacement of biomass feedstock by the refuse derived fuel (RDF) produced from the local municipal waste management facility was investigated. Therefore, over two years, several samples of the rejected fractions from the selective collection operations and the mechanical and biological treatment were collected at the waste management facility. These samples were characterized to evaluate the physical composition, proximate analysis, ultimate analysis, alkali metal and trace metal content, calorific, and chlorine contents. All data were statistically analyzed. Several important differences were found between the rejected fractions and biomass, namely moisture, volatile matter, and fixed carbon content. However, the calorific value is like the expected from common wood or forest wastes. Trace and hazardous elements were found to be below the standard for RDF. After the statistical analysis, it was found that not all parameters had a normal distribution. Non-parametric tests were performed and for all the parameters analyzed only moisture content, nitrogen, and hydrogen show to be dependent on the waste source. Overall, the results point out the feasibility to prepare RDF from rejected fractions to use as co-fuel in a biomass power plant.

1. INTRODUCTION

Today, energy plays a key role in the social and economic development of mankind. The environmental impacts of energy use are increasing awareness namely with global warming and natural resource depletion, with renewable energy sources taking an important role in the global strategy for sustainable development. Besides, it can help to improve the industry's competitiveness, at least in the long term, and can have a positive impact on regional development and employment. Renewable energy technologies are suitable for off-network services in remote areas of the world, without having to build

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or extend expensive and complex network infrastructures. The European policy is encouraging the substitution of traditional fuels in the road transport sector, so the need for electrical power production from biofuels is a key factor [1].

Biomass may be used as a local energy source in nearby power plants but usually, raw materials supply may not be enough to maintain continuous operation. The dedicated production of biomass in agricultural lands may be a drawback because fertile soil should be used for food production. One way to overcome this problem is the use of dedicated sustainable forest products, green wastes, or other waste streams as feedstock for power plants. Several authors reported the impacts of replacing traditional fuel, namely coal, by biomass and/or solid recovered fuels to decrease reliance on coal and its derivatives [2]. Moreover, solid fuels recovered from wastes can help comply with the European Union (EU) requirements related to waste management. As municipal solid waste (MSW) generation is increasing, EU environmental requirements become stricter, forcing governments and local authorities to implement reliable and effective waste management programs [3], such as a circular economy.

Legal requirements point out to the valorization of the rejected fractions from MSW management sites to optimize refuse-derived fuels (RDF) production. Production and utilization of the RDF increase the level of waste recovery, allows energy recovery, and transform the waste problem into a resource for the productive sector and to the community (e.g., waste tax reduction) [2]. With the valorization of these materials, is possible to avoid their landfill deposition and encourage policies of endogenous and renewable energies to use while decreasing greenhouse gases. The co-firing of biomass with other fuels for energy production may reduce some technical, economic, and environmental aspects like needs of feedstock supply or its lack of proximity to existing infrastructure. Moreover, it promotes compliance with the circular economy principles like recovery of intrinsic values of wastes namely the energy of rejected fractions from recycling operations [4]. The introduction of wastes in the process will help the boiler to maintain the vapor production to generate electricity and meet the goals of 30% replacement of fossil fuels by 2050 [5]. A net carbon offset through the replacement of coal with RDF (with less than 15% of water) may reach a net reduction in emissions of 0.4 tons CO_2/ton coal [6].

Other than combustion, wastes gasification and a further injection of the produced syngas into the boiler is another available technology. Conversion by gasification leads to higher electrical efficiency than conversion by combustion and produce more products as well like methanol, chemicals, or fuels like diesel [5]. Although this is a technology wide-spread for a long time, the waste application is still being developed for advanced uses of biomass and waste. Waste tires and RDF have been tested in pilot gasification units in terms of efficiency and syngas quality and it was found that depending on the composition of the input fuel and the gasification agent, it can produce syngas with lower heating value (*LHV*) from 5 to 15.2 MJ/Nm^3 [7].

RDFs from MSW have different physical and chemical properties depending on their sources, especially concerning their ash, chlorine, sulfur, and water contents. There are remarkable differences among RDF, and certain physical and chemical properties can set difficulties in the combustion process in cases where the RDF is introduced directly [6]. In some cases, the use of RDF may engage problems with the gaseous emissions and corrosion of the operational units resulting from high levels of chlorine or refractory organic matter in the recovered wastes [8–10]. Thus, it is necessary to produce RDF having more stable physical and chemical properties than the rejected fraction that is used for their manufacturing, knowing that they are cheaper than primary fuels. These fractions may be used in energy-intensive industrial sectors such as the cement industry, pulp and paper industry or thermal power plants [11].

In Portugal, the Decree-Law No. 64/2017 of June 12 defines a special and extraordinary legal regimen for the installation and exploitation of new self-subsistence or small scale biomass power plants, to preserve and maintain forests, minimize fire occurrence risks and their negative impacts. Such power plants have a local scale considering feedstock's reception points or mandatory licenses under the legal framework of electricity production from renewable resources. Within the study area, a biomass power plant with an electric output of 15 MW [12], consuming 140 000 tons of biomass yearly started its operation in 2019. With a biomass *LHV* of 13800 kJ/kg (30% moisture content), it is reasonable, from the energy point of view, to mix some RDF from the local waste management facility (with a higher *LHV*) with the forest biomass in the thermoelectric power plant [13].

This work aims to obtain a detailed characterization of the rejected fractions from the MSW local management facility and to study the viability of preparing RDF from its discarded fractions to understand the effects of replacing part of the biomass feedstock in the thermoelectric power plant.

2. MATERIAL AND METHODS

An inter-municipal entity of solid waste management is responsible for the municipal wastes collection and management of about 350 000 inhabitants from 19 municipalities, engaging an area of about 4.661 km^2. In this treatment, the site is also managed non-hazardous industrial solid wastes. The three main product areas are the sorting center for the multi-material recycling process, the mechanical and biological treatment for unsorted municipal wastes – miscellaneous urban solid wastes, and the landfill for ultimate disposal process. From the two major lines, the selective flow and the mechanical biological treatment, after recovering all the valuable fractions, it is sorted the refuse that recycling is impractical and it was used to produce RDF. Over two years – six sampling campaigns of the rejected fractions from the mechanical and biological treatment (MBTR) and the selective collection operation (SCR) in the management plant were characterized. Following the standard procedures, the samples were collected and prepared in a laboratory. The overall characterization included physical composition, proximate analysis, ultimate analysis, alkali-metal, and trace metal content. It was also evaluated the parameters defined in the standards for classifying RDF, the calorific potential, chlorine, and mercury contents. Original sample portions of about 15 kg of MBTR and 10 kg of SCR rejected streams were used. First, the physical characterization of rejected streams was made, evaluating the mass content of the food wastes, green wastes, wood, paper/cardboard, plastics (several plastic polymers), textiles, glass, iron materials, aluminum, non-magnetic metals, inerts, electric and electronics, and a final class of others (not classified above). Then, samples were cut and prepared by quartering and afterward hammer-milled and pressed. The proximate analysis was accomplished by the analysis of the moisture, volatile matter (VM), fixed carbon (FC), and ashes. Elemental analysis was performed with an I-S-ELEM (LECO) – model CHN628 for C, H, N, and 628 S for sulfur. Automatic bomb calorimetry was used to obtain the higher heating value (*HHV*). The *LHV* was calculated following CEN/TS 15400:2011, according to the hydrogen content evaluated in the elemental analysis. For the total chlorine content determination, a KOH absorption solution (0.2 mol/dm^3) was introduced in the calorimetric bomb and Mohr's method was used for quantification. The mercury was evaluated by a PSA 10.025 Millennium Merlin mercury analyzer (PS Analytical). Alkali metal and trace metal content were evaluated according to EN 14410:2011 and EN 15411:2011 standards using a Perkin Elmer atomic absorption spectrometer.

The statistics analysis was done by IBM Statistics V21.0. First, it was evaluated the existence of outliers following Dixon's Q test. After removing the suspected values the data normality was assessed with the Shapiro–Wilk test. Once some parameters did not follow a normal distribution, there were chosen non-parametric tests for further analysis, namely Spearman correlations to study the parameter associations and the Mann–Whitney test to study if the rejected fraction source controls the parameters under evaluation.

3. RESULTS AND DISCUSSION

Through the physical characterization of the rejected streams, it was noticed that the fractions had significantly different compositions, with SCR showing a higher percentage of plastics and paper, cardboard, and textiles. As expected, in MBTR, higher amounts of food and green wastes (biowastes) were found [14].

The proximate analysis is important once it gives, with relatively simple analytical methodologies, the fuel performance (Table 1). Moisture severely affects the produced gas quality and the thermal-chemical conversion. High moisture content leads to reduced *LHV* and low thermal input. Traditional combustion of biomass in the air is accomplished at 800–1000 °C and usually a moisture content of less than 50% is feasible, requiring otherwise the pre-drying of the feedstock [15]. Comparing the moisture of the fractions under study enables one to conclude that no important differences should be found within a mix of RDF with biomass in a thermal power plant. On the contrary, a positive synergistic effect can be observed with the reduction of the overall moisture of the boiler feed. The ash content of RDF may result in large amounts of leftover ash in the gasifier and leads to considerable energy losses and slagging, which may, in turn, restrict the efficiency and long term availability of the boiler [16]. VM and FC contents provide important information about the ignition and oxidation of the fuel to become an energy resource.

Table 1

Results of the proximate analysis and quality parameters of RDF for the rejected fractions (n = 7)

Fraction	Moisture [wb. %]	VM [wb. %]	Ash [wb. %]	FC [wb. %]	*LHV* [MJ/kg]	Cl [db. %]	Hg [mg/MJ][a]
MBTR	42.3±14.7	40.4±15.5	7.48±3.21	6.98±3.78	18.8±4.2	0.44±0.36	0.009
SCR	22.2±11.0	59.4±17.8	9.07±5.07	4.04±4.24	23.4±2.8	0.45±0.38	0.011

[a]These values represent the median of the six campaigns and their replicates. VM – volatile matter, FC – fixed carbon, *LHV* – lower heating value, wb – wet basis, db – dry basis.

VM and FC are substantially lower than the reference data for wood, while ashes are significantly higher. Wood is expected to have VM amounts ranging from 80% for oak or 60% for cherry, and an FC value of 10%, while ash may be less than 1% [15]. Nevertheless, it should not be generalized once depending on the species, the properties of wood change considerably. However, biomass briquettes, wood chips, wheat straw, or barley straw have values closer to rejected fractions under study, namely in terms of ash content [17]. The higher ash content of these materials may affect both the handling and processing costs and therefore the energy conversion cost [16]. Although there were found several differences in the wastes streams relative to wood or wood wastes, the *LHV* are similar to the ones reported for the species mentioned above. Moreover, chlorine is a factor that may affect the long-term boiler availability due to its extremely corrosive behavior, thus its concentration must be constantly monitored when biogenic fuels are used [18]. In this type of rejected fractions, the chlorine content source seems to be the polyvinylchloride (PVC) and the measured Cl quantity is lower than obtained by other authors and not expected to cause any significant technical disorders or environmental problems [19]. Mercury content results in the six campaigns are around 0.010 mg/MJ, for both streams. These results are similar to those found by Vounatsos et al. [18] that studied materials derived from packaging waste, mainly composed of plastic and paper.

According to the RDF Portuguese standard [20], the classification of the potential products that can be prepared from these wastes' streams are class 2 concerning their heating value and chlorine content and as class 1 concerning their mercury concentration. Italian standards for RDF define as threshold values: 15 MJ/kg for *LHV* (19 MJ/kg for higher quality RDF), 25% for moisture, and 20% for ashes [21]. In Sweden, RDF

LHV values must be between 23.9 and 31.4 MJ/kg and the moisture content must be below 10% for light fuel or 30% for special fuels [22]. The ultimate analysis provides information about wastes carbon, hydrogen, nitrogen, sulfur, and oxygen content, allowing an estimation of its heating value and mass balance. The results are shown in Table 2.

Table 2

Results of the ultimate analysis of rejected fractions ($n = 7$)

Fraction	C [%]	H [%]	N [%]	S [%]	O [%]	H/C	O/C
MBTR	40.28±5.54	5.22±0.73	1.18±0.28	0.22±0.04	50.14±6.49	0.138	1.25
SCR	45.43±3.02	6.12±0.47	0.56±0.37	0.48±0.40	57.02±5.80	0.141	1.26

Carbon and hydrogen are the main elements concerning the heating potential of fuels. Oxygen is also present in organic materials that integrate the fuels (partially bonded to hydrogen as water), thus its presence decreases the fuel heating value. Lower carbon content reduces the energy value of fuel once carbon–carbon bonds have higher energy than bonds like carbon–oxygen and carbon–hydrogen.

According to several authors, RDF may have a lower carbon content than biomass, namely from species like cypress and beech, and a higher content of oxygen. For such species, values of carbon are expected to be around 55.0% and 51.6%, respectively [23], while in both fractions of wastes rejected fractions the carbon content was, on average, 40.3±5.5% and 45.4±3.0% for MBTR and SCR, respectively (Table 2). The hydrogen content evaluated in the rejected fractions is slightly lower than the described for biomass, namely 5.22±0.73%, and 6.12±0.47%, for MBTR and SCR, respectively. For cypress, the hydrogen content is around 6.5% and for beech, 6.3%. Considering the major elements, oxygen is much higher (about 57% MBTR and 50% SCR) in wastes that in wood. Due to the different types of biomass and consequent properties variability, it is not possible to establish a representative biomass classification [4]. Through the van Krevelen diagram [15] (that summarizes the type of biomass according to hydrogen/carbon and oxygen/carbon ratios) it is possible to verify that wastes move away from biomass behavior, where the H/C ratio ranges from 0.12 to 0.16 and the O/C ratio between 0.4 and 0.9. The most important difference is the O/C ratio that in the case of RDF is considered superior in the biomass, representing lower content of carbon. The probable impact of higher amounts of hydrogen and oxygen is the reduction of the energy content of the fuel materials [15]. The alkali metals are a family of elements that represent some concern in combustion equipment due to the chemical transformations that lead to adhesive liquid formations that may produce fouling in the furnace and boiler plant [15]. Furthermore, heavy metals may harm human health and the environment due to their cumulative toxic properties. Finland standards point to maximum levels of 0.5% concerning sodium and potassium in RDF [21]. As can be seen in Table 3, these alkali metals do not exceed such values. It was also found that other metals assessed are below the limit references for quality assurance [2, 21], namely chromium, nickel, copper, or lead. Similar studies found that Pb and Zn were the heavy metals presented in the highest concentration, followed by Cr and Cu [22]. Generally, the values found in this study are somewhat below the ones reported by other authors. In all cases, it seems that these values were difficult to calculate due to the low concentrations and the sample heterogeneity, which are reflected in the high values of the standard deviation. This variation can cause some difficulties to predict compliance with the RDF quality standards. When comparing with feedstock recovered from forest or garden biowaste [17], is possible to identify higher amounts of metals that probably can have an impact in the composition of the ashes resulting from the combustion.

Table 3

Metal content in the rejected fractions in the dry basis ($n = 7$)

Metal	MBTR	SCR
Ca, %	0.48–4.4	0.61–7.1
Fe, %	0.064–0.63	0.050–0.44
K, %	0.080–0.73	0.030–0.21
Mg, %	0.030–0.28	0.020–0.11
Na, %	0.050–0.30	0.030–0.10
Cd, mg/kg	0.23–1.2	0.23–3.5
Cr, mg/kg	3.4–33	2.3–32
Cu, mg/kg	6.8–29	6.5–19
Mn, mg/kg	5.7–72	4.4–33
Ni, mg/kg	0.78–3.1	0.31–1.7
Pb, mg/kg	1.6–27	1.9–22
Zn, mg/kg	200–1200	200–2600

Besides the selective collection, in some cases, the heavy metals content such as Zn and Cu, were higher in this stream (SCR) than in the MBTR indicating that their presence was independent of the fractions source. It was observed that SCR stream is rich in plastic and paper, which may contribute to the Zn and Cu high levels, respectively [24]. Genon and Brizio [25] confirmed that the heavy metals content in the RDF can be quite variable and lead to different conclusions about the advantages of using these wastes as alternative fuels in terms of pollutants released, indicating that it cannot be assumed a general impact of these fuels in the environment.

Results from the twelve samples were statistically analyzed according to the Spearman correlations to evaluate if there are significant correlations between properties, with a confidence level of 95% ($p = 0.05$) or 99% ($p = 0.01$). Correlations measure the degree of linear association between parameters through the negative or positive impact of the rejected stream properties [33]. It was verified that the heating value has a strong positive correlation with VM ($p = 0.01$) and therefore with carbon and hydrogen content. This result indicates that wastes with low VM will have low heating value and their utilization as fuels are not feasible. It was also found a strong negative correlation between the heating value with the moisture and nitrogen content. Samples that had higher moisture content that came from the MBTR had lower heating value. Thus, an easy way to select the wastes to be used for fuel/RDF is to attend the VM value. Additionally, it was also noted that high nitrogen content decreases the heating value, which indicated that biowastes must be avoided in RDF. In general, wastes suitable for fuels, with high carbon and hydrogen content and low nitrogen and moisture content arise from SCR. It is also interesting to see that moisture has significant correlations ($p = 0.05$) with ultimate analysis, carbon, hydrogen, and nitrogen contents having the formers a negative correlation and the last one a positive. The calcium concentrations showed a strong positive correlation with the waste ashes and fixed carbon, and also that the trace metals content is correlated between them. Therefore, if one of the trace metals is presented in a high concentration, it points to that the others will also be present in a high concentration. These correlations are important to infer about possible pollutions problems.

With the Mann–Whitney U-test, where the null hypothesis was that the parameters were similar independently of the rejected fraction origin (MBTR or SCR), it was found that for moisture, hydrogen, and nitrogen content the null hypothesis should be rejected ($p < 0.05$). For the other parameters, it was exhibited that their content was independent of the source: the mechanical and biological treatment or the selective collection operations.

The use of rejected fractions implies the sorting to leave a combustible material, mainly by removing wet biodegradables or inert like stones, glass, or scrap metals from the income streams. Therefore, several operations are needed to prepare a homogeneous fuel. Among others, it can be mentioned sieving, separation, crushing, screening, and picking. However, the most important of all should be drying, using natural or mechanical insufflation of air to achieve a moisture value below 10%, an acceptable value for wood and biomass wastes that are the feedstock of biomass power plant facilities.

4. CONCLUSIONS

In the waste management plant under study, there are several unitary operations to recover the valuable fraction from municipal solid wastes. However, from these operations, rejected fractions arise that are dumped in landfills. Keeping in mind the need to perform their valorization, it was performed a characterization of the fractions from the unsorted collection and selective collection operations, after previous materials recovery. Attendant to the purpose to produce an RDF for further valorization as co-fuel in a biomass power plant, from this characterization, the following conclusions were withdrawn:

- The fraction of waste materials under study have high heterogeneity.
- The moisture has high values suggesting the need for the previous drying although biomass power plants use as feedstock wood and wood wastes usually with values in the same order of magnitude.
- According to NP 4486:2008, the classification of the potential RDF should be PCI 2, Cl 2, Hg 1.
- Comparing with wood and wood wastes, the RDF have lower volatile matter and fixed carbon content but higher values of ashes.
- The mineral composition of rejected fractions accomplishes European regulations and can be compared with materials nowadays currently produced.
- The content of nitrogen has a negative influence in the RDF heating value, point out to the need for separation of biowastes previous to the RDF production.
- The rejected fractions from both MBTR and SCR do not have a significant influence on the final RDF properties.

Obtained results show that the rejected materials have a very interesting potential, namely if blended, to produce RDF to use in a biomass power plant.

ACKNOWLEDGEMENTS

The authors thank the Instituto Politécnico de Viseu and CI&DETS for their support.

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