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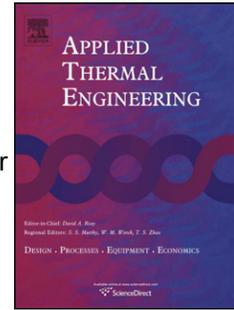
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ANALYSIS AND COMPARISON OF MUNICIPAL SOLID WASTE AND REJECT FRACTION AS FUELS FOR INCINERATION PLANTS

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ABSTRACT

Municipal solid waste, before (MSW) and after (RDF) the material recovery carried out in mechanical-biological treatment plants (MBT plants), have been analyzed in order to compare the efficiency of incineration of both fractions. RDF of MBT plants is about 67 % by volume of the initial MSW and is usually landfilled; in order to minimize the amount of landfilled waste, incineration with energy recovery has been suggested so main energetic properties of both streams, MSW and RDF, have been determined. Current data for MSW and RDF compositions have been obtained from 36 samples of 250 kg, taken in 10 different MBT plants, in the area of Castilla y León (Spain). Gross and low calorific values, non-combustible material percentage and water content of MSW and RDF have been measured for each fraction in which waste was classified. Obtained results show high percentages of combustible materials such as plastics or cellulose, which raise the energetic content to 10160 kJ/kg for MSW and to 18281 kJ/kg for RDF. The highest low calorific value (similar to that for some types of wood) corresponds to RDF, so its incineration will be more profitable than using MSW as fuel.

Keywords: Municipal solid waste, Mechanical-biological treatment, Refuse derived fuel, Energy recovery, Incineration.

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1. INTRODUCTION

Nowadays one of the most important challenges for chemical engineering is to convert wastes into raw materials for other processes. This is the case of municipal solid waste (MSW), continuously increasing with more than 260 million of metric tons generated last year in Europe [1]. For this reason waste management policies in the European Union evolve towards generation minimization and promotion of recycling, reuse and energy recovery prior to disposal on landfills. In this way hundreds of waste treatment facilities (mechanical-biological treatment plants or MBT plants) have been installed in European countries in the last decades [2-6].

The main objective of these facilities is to divide the received MSW stream into its different fractions in order to subject them to specific treatments. Organic fraction of municipal solid waste (OFMSW) and recyclable materials such as paper, plastic containers, cans, etc. are removed; the rest of the waste stream, known as reject fraction, is usually disposed on landfills [7]. In general, landfills are placed beside MBT plants and are designed to accommodate the reject fraction generated over 10-15 years. However, according to the mass balances, nowadays the reject fraction represents 2/3 of the initial volume of waste, an amount slightly higher than expected. Consequently, the dumps are full even 5 years ahead the schedule and new locations should be sought. In order to solve these problems of space and the loss of a lot of material that might be a good fuel, incineration with energy recovery has been suggested.

Incineration can reduce the waste volume up to 95 % although is not a very popular process. Nevertheless, the more stringent requirements on air pollution can be controlled using correctly the existing technology [8]. Incineration of MSW is the most implemented treatment option in populous countries such as China [9]. Japan is the country with the

highest number of waste incineration plants, about 1900 facilities, 190 of them with power generation [10]; it is followed by the European Union's countries, mainly France, and the United States. According to previous works on integrated waste management, MSW have a high calorific value allowing the incineration with great energy recovery although, in accordance with the current strategies [11], incineration should be done once recyclable materials have been recovered, i.e. to the reject fraction from MBT plants also named refuse derived fuel (RDF).

The main advantages of RDF incineration over using MSW as fuel are better efficiency of energy recovery and better quality of flue gases by significant reduction of heavy metals in the fly ashes [12]. Both advantages are closely related to the composition of incinerator feedstocks, however, the latest data of MSW characterizations in Spain were published in 1999 [13] and for RDF have never been available.

The aim of this work was, therefore, to investigate the unknown composition of the reject fraction from MBT plants as well as the updating of MSW data, in order to prove the advantages of RDF incineration over MSW incineration in function of the composition. The most important properties from the energetic standpoint such as calorific values, combustible fractions or water content, were measured for this purpose. By means of the establishment of these values for the two streams used as incinerator fuels, MSW and RDF, combustion effectiveness might be assessed in future.

On the other hand, once the qualitative and quantitative composition of MSW and RDF has been accurately determined, waste treatments performed in MBT plants could be modified and adapted to them, with the purpose of improving the overall performance.

2. EXPERIMENTAL PROCEDURE

2.1. Description of MBT plants.

Experiments were performed by triplicate on 36 different samples, 18 of RDF and 18 of MSW, collected in 10 MBT plants sited in the area of Castilla y León, Spain. Castilla y León is the Spain's largest Region with a total surface of 94224 km², and 2.5 million of inhabitants. Main technical features of these facilities were described in a previous work [14] and the operating diagram is shown in figure 1. In the first step, a manual removal of bulky elements, mainly cardboard, is performed to avoid blockages. Due to the small size of the organic matter, it is removed as the fine fraction of rotary screens called trommels with 80-90 mm as holes size. This organic fraction of municipal solid waste (OFMSW) is stabilized by means of biological treatments, composting or anaerobic digestion, to produce a soil fertilizer (compost) or biogas for energy generation respectively. In 6 of the 10 studied MBT plants, composting is used as OFMSW treatment; in 2 of them use anaerobic reactors and both treatments are simultaneously used in the rest of MBT plants. Coarse fraction from the first trommel, upper than 80 mm, is carried to the second manual selection where recyclable materials such as paper, plastic containers and glass are recovered. After passing through magnetic and Foucault separators, ferric metals and aluminium are removed. The remaining material, known as reject fraction, is sent to the adjoining landfill.

2.2. Waste sampling and characterization

Visits were conducted in different seasons and working days (excluding Mondays since MSW are not collected on Sundays). Approximately 1000 kg for each analysis were taken by mechanical shoveling at the beginning and end of the mechanical-biological

treatment process. Samples were spread to form a circle and divided into quarters; two opposite sectors were taken and a new circle was formed which was again divided into quarters; the final sample (approximately 250 kg) was composed of two opposite sectors once more. In order to determine the composition, these samples were manually sorted and weighted *in situ*; plastics were differentiated by their characteristic plastic identification number (PIN) printed on them. Because the Spanish or European standard methodology has not been established, waste materials present in MSW or RDF samples were divided into 19 categories according to the MODECOM procedure [15]:

- Biodegradable matter (mainly food waste) usually named organic matter
- Paper and cardboard
- Plastics, divided into:
 - PET (polyethylene terephthalate) PIN 01
 - HDPE (high density polyethylene) PIN 02
 - PVC (polyvinyl chloride) PIN 03
 - LDPE (low density polyethylene) PIN 04
 - Mix (the rest of kinds) PIN 05, 06 and 07
- Glass
- Ferrous metals
- Non ferrous metals
- Cellulose
- Tetrabricks
- Textiles (used clothes)
- Wood
- Rubber
- Batteries
- Garden wastes

- Electronics
- Building wastes

2.3. Analytical methods

For moisture and gross calorific value (GCV) determination, 3 samples of each category were taken from each MBT plant. In order to obtain reliable values for each category, different samples were taken, i.e. different containers for each plastic fraction or different fabrics for textile one. Homogeneous samples of organic matter were obtained by means of above mentioned method, in this case initial sample was 1 kg.

Moisture was measured on 250 g of sample approximately, by the weight lost after oven drying at 105 °C for 24 hours or at 70 °C for 5 days in the case of plastics, cellulose and tetrabricks. All analyses were carried out by triplicate.

After drying, approximately 1 g of each fraction perfectly homogenized was crushed and inserted into a calorimeter system IKA C200 for GCV determination. Periodic calibrations with benzoic acid (GCV = 26460 kJ/kg) were performed. All analyses were carried out by triplicate as well.

Low calorific value (LCV) was obtained from GCV by means of the equation: $LCV = GCV - K \cdot W$ [16]; where W is the mass fraction of water formed during combustion of the fuel and K is the evaporation latent heat of water at 20 °C, which is 2453,5 kJ/kg of water [17]. Gross and low calorific values of each of the combustible categories of waste (organic matter, paper and cardboard, plastics, cellulose, tetrabricks, textiles and wood) were measured and calculated respectively so that, using the composition data of MSW and RDF, calorific value of each stream can be determined.

Experimental results obtained for GCV and LCV in this way are measured as kJ/kg of dry waste. GCV and LCV expressed as kJ/kg of waste (including water as component of the waste) were calculated by multiplying experimental results by $(1 - \text{kg water/kg waste})$. GCV and LCV expressed as kJ/kg of dry-ash free waste (excluding water and ashes as component of the waste) were calculated by dividing experimental results by $(1 - \text{kg ashes/kg dry waste})$.

Considering the sample size, $n=18$, the rejection or acceptance of data for obtaining average and standard deviation, have been made in accordance with the Student's t -distribution for 95 % as confidence interval and p -value (two-tailed) = 0.023.

3. RESULTS AND DISCUSSION

3.1. *Composition of fuels.*

After data processing, average compositions for both, MSW and RDF streams, in the area which is target of this work have been obtained. Weight percentage averages of each fraction forming MSW and RDF are summarized in table 1. Standard deviations for these data are also shown in table 1. Despite working with such heterogeneous samples, attending to composition results, standard deviations of majority constituents are not as substantial as it could be expected. However, standard deviation and average of less abundant fractions have approximately the same values and must be taken carefully in the mass balances.

According to data provided by MBT plants, RDF represents 66.7 % of the initial MSW volume. Once individual percentage of each fraction has been found, the specific weight of both streams can be obtained by means of the fraction specific weights [18]. Then, RDF is approximately 42 % by weight of the initial amount of wastes and its specific weight is 130.8 kg/m³ which is lower than achieved for MSW, 208.0 kg/m³.

A comparison between weight composition of MSW and RDF (figure 2) shows that the most significant difference is related to biodegradable matter presence: while it is the main constituent in MBT plants inputs (56.26 %), it is only 23.71 % of the outputs. A substantial recovery is carried out in trommels; approximately 82 % of organic matter and 97 % of garden wastes are removed from MSW stream and they are taken to bioreactors or tunnels where they will be stabilized biologically. However, despite the efforts made in waste management aimed at minimizing the presence of biodegradable wastes in landfills in recent years, the amount of organic matter disposed in landfills is still important. Therefore, levels required by the EU directive 1999/31/CE for year 2016 (a reduction of 65 % of the total amount by weight of biodegradable wastes produced in 1995 [19]) will be hardly achieved.

MSW composition provides valuable information about the population behavior. In the past, a higher paper percentage in MSW, i.e. a high consumption, used to be considered a good indicator of the country industrialization. However, nowadays in developed countries, paper consumption has decreased and the plastics one has increased, regarding last decade data. Moreover, paper, plastics and glass percentages in MSW are not strictly proportional to their consumption since they are selectively collected. According to data collected in table 1, this selective collection is far from being complete and recyclable materials, mainly paper and plastics, are widely present in MSW. On the other hand, despite the recovery taking place in MBT plants, 15.24 % and 10.20 % for paper and

plastics respectively, they are the main components of RDF along with organic matter: each one of them represents approximately 25 % (figure 2). It should be noted that the recovery of these materials is manually performed and the tons of MSW, treated per year and worker, ranges from 2500 to 10000. Therefore, as said previously, some standard deviations of the materials composition are high values, mainly in the less abundant fractions.

Low density polyethylene (LDPE) always will be present in large proportions since is used in garbage bags. Greater amounts of high density polyethylene (HDPE) and polyethylene terephthalate (PET), both above 40 %, are recovered in MBT plants because they are usually found with container form making the manually collection easier. A low percentage of polyvinyl chloride (PVC) appears in both fractions showing a tendency to give up its use according to European recommendations (EU Directive 78/142/EEC) [20].

Although glass appears in low proportion in the input, its retrieval in MBT plants is over 90 % and the output percentage is even lower. Likewise, 47 % of metals are removed from MSW by means of magnets and Foucault separators and 23.31 % of tetrabricks are manually removed. Considering data from table 1, ferrous and non ferrous metals have practically the same recovery yield.

Used clothes (textiles fraction) are not recycled by population, containers for this purpose have not been installed in the studied area and they are not recovered in MBT plants either, so the same amount that is in the MSW will be at the RDF. However, despite of having specific containers to batteries recycling, during the experiment at least one battery was found in each of the samples. Because of its small size, weight percentages are not very high unlike its pollutant effect. Their presence in MSW might cause high levels of heavy metals in compost whose application to soils could be dangerous [21].

3.2. Fuel moisture

In addition, water content of wastes is relevant information from incineration standpoint; some studies show a decrease in the combustion efficiency due to the increase of the moisture in waste as well as its influence on gases emission such as CO, SO₂, NO, and NO₂ [22]. Average and standard deviation of moisture data for main categories are summarized in table 2. Significant differences between both streams have been found: each MSW fraction contains more water than the same category in RDF, as result of moisture losing in mechanical processes of MBT plants. Organic matter, paper and textiles are the materials containing more water in received MSW; however, moisture datum of paper in the output is not so high. This fact is explained by the greater recovery of cardboard over paper since the former is wetter. According to experimental data and considering 60 % of water for garden waste reported in literature [18], total moisture percentage of both streams have been calculated resulting 46.46 % for MSW and 22.07 % for RDF. Humidity loss during the mechanical treatment is 52.51 %.

3.3. Fuel calorific values

Gross calorific values obtained for combustible materials from RDF and MSW streams are summarized in table 3. Non-combustible materials in fuels determined as combustion ashes were also weighed; data are shown in table 3.

HDPE and cellulose have the highest energetic content above 45000 kJ/kg, LDPE and the fraction of plastics named "mix", with 40000 kJ/kg follow them closely. In a lower level, with calorific values around 20000 kJ/kg, are materials such as tetrabricks, textiles, PET and wood. Finally paper and organic matter have the lowest calorific value, 15000

kJ/kg approximately. Although the calorific value of fractions such as cellulose, tetrabricks, HDPE, LDPE, PET, and PVC have been measured for the first time in this work, the rest of the obtained values are slightly higher than calorific values previously available in literature [18] and [23].

Regarding the amount of ashes generated after combustion of waste fractions, table 3, the cases of tetrabricks and paper are worth mentioning. Cardboard and aluminium are the main constituents of tetrabricks so high metal content is reflected in the ashes percentage of this fraction, 10.21 %. Ashes from paper fraction (9.56 %) have a metal nature as well, because of the high quantity of inks in newspaper and magazines. Assuming metals, glass and building waste are incombustible materials, and considering the data composition previously shown, non-combustible fraction (weight percentage on dry basis) was 15.23 % for MSW and 10.10 % for RDF. The lower production of ashes is, therefore, one of the advantages of RDF incineration: ashes amount generated in MSW combustion is more than the 50 % of ashes amount generated in RDF incineration thus higher space requirements in the security dumps are necessary for MSW ashes.

Heavy metals such as zinc, cadmium or mercury may appear in the ashes of the combustion process due to the batteries presence although, according to this work, a large amount of them is not expected. Nevertheless, they should be disposed in a security dump.

3.4. Comparative assessment of MSW and RDF as fuels

Once known the current real composition of MSW and RDF, and given the individual qualities of each fraction, the main properties, from energy standpoint, might be calculated (table 4).

With the aim of comparing calorific data with those previously reported in the literature, low calorific values for both streams, MSW and RDF, have been calculated. Low calorific value gives very useful information about the theoretical maximum energy that could be obtained from the combustion real process since, as previously said, the latent heat of vaporization of water formed during combustion should be subtracted. Taking into account wastes characterizations obtained in this work (table 1) and elemental composition of each fraction which constitutes them [18], approximate chemical formula was obtained for each stream which is summarized in table 5. Water as combustion product can be calculated from hydrogen amount in waste: kg of water as combustion product = kg of hydrogen per unit weight of the fuel burnt \times 9, because, according to the water formation reaction, 1 part by weight of hydrogen gives 9 parts by weight of water. Water as combustion product will be, therefore, 0.623 kg/kg burned MSW and 0.627 kg/kg burned RDF; results for LCV are shown in table 4.

According to their energy content, both streams, MSW and RDF, could be used as incinerator fuels since both LCVs are higher than 7000 kJ/kg [9]. However, incineration of RDF will be more profitable than incineration of MSW because of the higher water content of this stream, gross calorific value in kJ per kg of waste is 79.9 % greater for RDF than for MSW. Considering gross calorific value in kJ per kg of dry waste, RDF value is still 23.6 % higher than MSW value because of the greater percentage of materials with high calorific value such as LDPE, plastic mix and cellulose in RDF stream.

Low calorific value of analyzed MSW, 8326 kJ/kg, is higher than values previously reported in literature for Taiwan 7568 kJ/kg [12] and China, which results ranging from 2855 kJ/kg to 6710 kJ/kg [9]. On the other hand, the highest values have been found in countries such as U.S.A 11575 kJ/kg [18], United Kingdom 10600 kJ/kg [24] or India 9999 kJ/kg [25]. Low calorific value for RDF, 16661 kJ/kg, is certainly higher than calorific value

of the same fraction in Italian MBT plants 10110 kJ/kg [23] and in Taiwanese ones 13733 kJ/kg [12]. Differences could be due to the different composition of MSW and RDF in the studied countries.

Therefore, RDF is better combustible than MSW because of its low calorific value is double. In addition, an increase in the energy recovery for RDF can be achieved by improvement in removal systems of the organic matter in MBT plants, because this fraction has one of the lowest calorific values and shows approximately 50 % of moisture, which means RDF is more suitable for using in incinerators than MSW again. In fact, GCV of RDF is on the order of values of some types of wood such as pine 20583 kJ/kg, or ilex, 18475 kJ/kg [26].

3.5. Environmental impact of MSW and RDF incineration

In the studied area, waste incineration is not carried out at the moment; this work proves that might be a profitable process from energetic point of view although public acceptance of such facilities is always difficult.

However, it has been demonstrated that by using adequate technology, concentration of pollutants at incinerator stacks can meet the European requirements [27] as shown the work of Consonni et al. [28]. In the case of the most unpopular pollutants, dioxins and furans, an appropriate system design and an end-of-pipe treatment can make these compounds disappear from the final flue gases [29]. According to Kuo et al. [30], technology installed in Taiwan for flue gases treatment, especially for NO_x, SO_x, CO, HCl and heavy metals (Pb, Cd and Hg) is obtaining good results in the gaseous pollution control. Moreover, energy recovered in waste incineration may contribute to reduce the emission of greenhouse gases by the primary energy saving when it is combined with

other processes [31], [32]. According to Chang et al. [12], the quality of flue gas in RDF incineration is better than using MSW as fuel, since the presence of heavy metals in the fly ash is lower as well.

Therefore, although a more detailed study is necessary; in this work RDF incineration is suggested as the best alternative to landfilling in the studied area subject to compliance with the environmental requirements.

4. CONCLUSIONS

Attending to the obtained results after analyzing 36 different samples of MSW and RDF from 10 MBT plants, some conclusions can be extracted. Composition of both streams is now known and any property can be determined by measurement of individual values. In this work properties related to energy recovery have been calculated in order to establish the advantages of RDF incineration over MSW incineration. RDF obtained after processes carried out in MBT plants has a higher low calorific value, greater content of combustible fractions and less moisture than MSW. Besides these values means that RDF is better fuel than MSW; burning MSW entails a loss of the recyclable materials recovered in MBT plants which contradicts the European waste policies.

Additionally, incineration of waste has the advantage of volume reduction that in this case involves less space requirement in landfills. Moreover, despite of the mechanical removing that takes place in MBT plants by means of trommel screens, organic matter still appears in RDF in high proportions and, if this fraction is deposited in landfills may violate the European Directive 1999/31/CE about biodegradable wastes; incineration of RDF could solve this problem as well.

Results reported in this work provide very useful information for the MBT plants design which is facilitated by the complete characterization of the fractions involved. Facilities that are already installed can improve their performance with minor modifications adapted to these results.

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Figure captions

Figure 1. Typical operating diagram of the studied MBT plants.

Figure 2. Present composition of MSW (MBT plant input) and RDF (MBT plant output).

Table captions

Table 1. Composition of MSW and RDF, weight percentages.

Table 2. Water content in weight percentages.

Table 3. Calorific value and non-combustible material weight percentage of individual combustible fractions (dry basis).

Table 4. Summary table of the main properties of fuels.

Table 5. Elemental composition of MSW and RDF.

Highlights of “Analysis And Comparison Of Municipal Solid Waste And Reject Fraction As Fuels For Incineration Plants” (Reference: ATE 3506)

- > MSW and RDF composition of 10 MBT plants have been obtained on 36 samples.
- > Main energy properties of both streams have been determined.
- > RDF as fuel shows higher GCV and LCV, lower moisture and lower ashes amount than MSW.
- > Both, MSW and RDF, are good fuels although RDF incineration is more profitable than the MSW's.

Table 1. Composition of MSW and RDF, weight percentages.

Categories	MSW composition		RDF composition	
	Average (%)	Std. Dev. (%)	Average (%)	Std. Dev. (%)
Organic matter	56.26	7.44	23.71	7.84
Paper and cardboard	13.80	5.52	27.91	4.73
Plastics	10.67	3.08	24.50	4.25
HDPE	0.75	0.39	0.99	0.73
PET	1.46	0.52	1.87	0.85
LDPE	5.56	1.72	10.93	3.29
Mix	2.90	2.07	10.62	3.41
PVC	0.00	0.01	0.08	0.19
Glass	3.28	1.45	0.48	0.45
Ferrous metals	2.46	1.35	3.10	1.99
Non ferrous metals	0.50	0.46	0.61	0.51
Cellulose	4.06	1.90	5.76	2.33
Tetrabricks	1.18	0.37	2.16	1.77
Textiles	3.57	2.03	8.65	3.76
Wood	1.33	1.06	2.18	1.37
Rubber	0.24	0.62	0.03	0.10
Batteries	0.01	0.04	0.00*	0.00
Garden wastes	1.84	2.10	0.14	0.37
Electronics	0.12	0.23	0.34	0.50
Building wastes	0.69	1.04	0.48	0.45

* Batteries were found in RDF but weight percentage is < 0.01%

Table 2. Water content in weight percentages

Categories	Water content in MSW		Water content in RDF	
	Average (%)	Std. Dev. (%)	Average (%)	Std. Dev. (%)
Organic matter	58.33	1.43	42.26	8.20
Paper and cardboard	55.59	3.18	16.72	1.31
Plastics	22.31		15.14	
HDPE	17.07	1.46	25.56	2.74
PET	8.27	0.75	7.31	0.10
LDPE	34.57	6.58	24.58	15.69
Mix	7.23	2.91	5.84	0.10
Glass	1.12	0.58	1.05	1.61
Metals	2.64	2.54	2.52	1.73
Cellulose	6.64	3.19	5.10	2.21
Tetrabricks	32.87	2.69	29.74	16.52
Textiles	46.00	2.39	28.45	9.86
Wood	5.55	4.90	4.70	3.80
Building wastes	0.12	0.58	0.13	0.08

Table 3. Calorific value and non-combustible material weight percentage of individual combustible fraction (dry basis).

Categories	Gross calorific value		Non-combustible material	
	Average (kJ/kg)	Std. Dev. (kJ/kg)	Average (%)	Std. Dev. (%)
Organic matter	14905.0	282.8	1.82	0.45
Paper and cardboard	14739.9	2654.7	9.56	3.06
Plastics				
HDPE	45670.4	443.6	0.65	0.42
PET	22995.0	16.1	0.20	0.25
LDPE	41269.5	3043.3	2.09	1.43
Mix	41203.8	2820.9	2.87	2.53
Cellulose	45552.0	330.9	0.15	0.02
Tetrabricks	23557.1	154.5	10.21	2.53
Textiles	21298.2	5226.0	2.84	1.61
Wood	18825.0	20.3	1.25	0.04

Table 4. Summary table of the main properties of fuels.

	MSW	RDF
Gross calorific value (kJ/kg of waste)	10159.8	18280.8
Gross calorific value (kJ/kg of dry waste)	18973.1	23444.6
Gross calorific value (kJ/kg of dry-ash free waste)	26518.9	26948.7
Low calorific value (kJ/kg of waste)	8325.9	16660.7
Low calorific value (kJ/kg of dry waste)	17677.1	22061.2
Low calorific value (kJ/kg of dry-ash free waste)	24990.2	25409.9
Moisture (%)	46.46	22.07
Non-combustible material (% weight dry basis)	15.23	10.10
Specific weight (kg/m ³)	208.0	130.8

Table 5. Elemental composition of MSW and RDF

		C	H	O	N	S	Ashes
Weigh percentage (dry basis)	MSW	41.37	5.36	29.01	1.40	0.21	22.65
	RDF	45.09	5.78	30.94	0.94	0.15	17.11
Chemical formula (dry-ash free basis)	MSW	3.45	5.36	1.81	0.10	0.01	
	RDF	3.76	5.78	1.93	0.07	0.00	

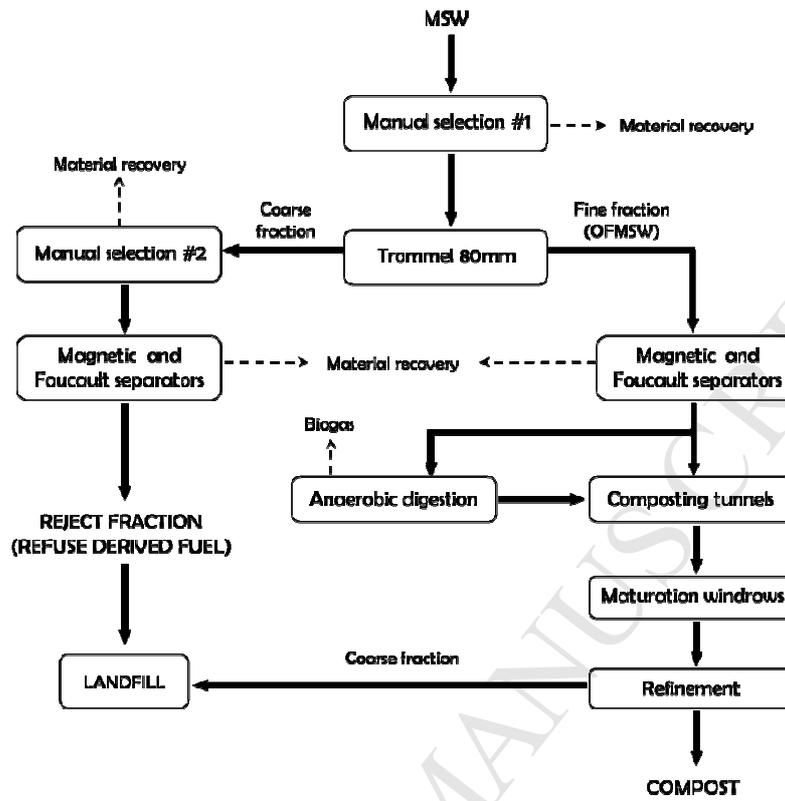


Figure 1. Typical operating diagram of the studied MBT plants.

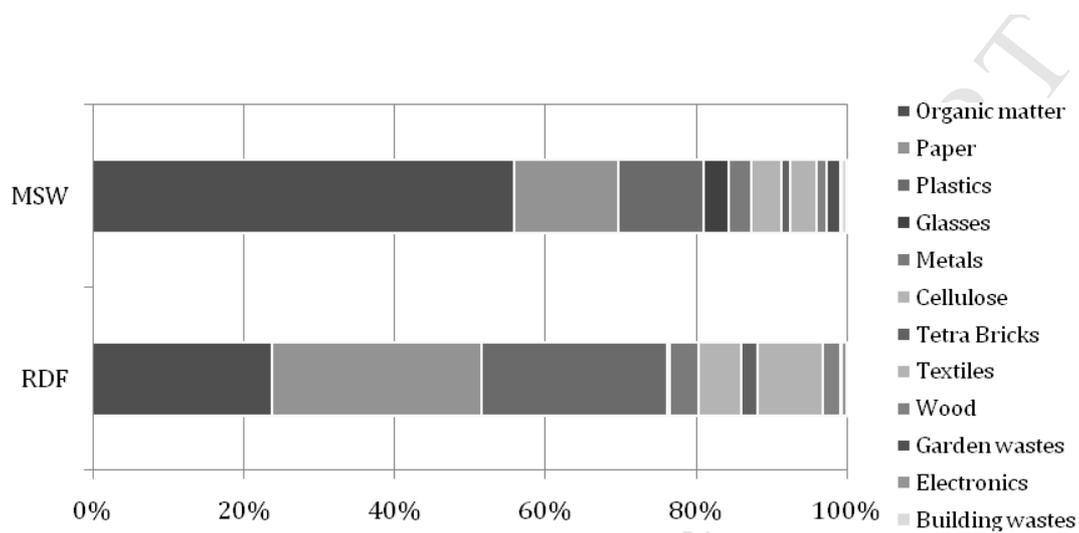


Figure 2. Present composition of MSW (MBT plant input) and RDF (MBT plant output).