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Analysis of refuse-derived fuel from the municipal solid waste reject fraction and its compliance with quality standards

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ABSTRACT

The final disposal of the Municipal Solid Waste is still a problem in many countries. The lack of space, the generation of leachate, and the emission of greenhouse gases as well as the requirements of the new legislation on waste dissuade the administrations involved from using the landfill option as a possible means of final disposal of MSW. The terms of the European Legislation on waste management and energy encourage member states to develop waste recovery techniques before sending it to a landfill. Therefore, member states have introduced source separation and mechanical-biological treatment to separate biodegradable recovery fractions (organic, paper-cardboard, plastic packaging, and glass) from the reject fraction, which is afterwards disposed of in landfills. One of the main aims of this study is to analyse the energy recovery properties of the reject fraction from a biological-mechanical treatment plant in Spain. For this purpose, this work presents a physical and chemical characterization of waste reject fraction from a real mechanical-biological treatment plant as well as the metal and halogen content. Additionally, the quality standards of the refused derived fuel processed at the laboratory and the atmospheric emissions of this type of fuel have been determined.

1. Introduction

The final disposal of Municipal Solid Waste (MSW) is still a problem in many countries, including European countries. The increasing price of raw materials as well as the lack of space for new landfills, the problems arising from leachate and the restrictions imposed by the European regulations mean that a number of waste strategies have been produced and are awaiting implementation (Murphy and McKeogh, 2004). A waste hierarchy suggesting the environmental preference of recycling over incineration over landfilling is often put forward and used in waste policy making (Finnveden et al., 2005). From an energy recovery viewpoint, Arafat et al. (2013) found that it is best to recycle paper, wood and plastics; to anaerobically digest food and yard wastes; and to incinerate textile waste. Eriksson et al. (2005) showed that reduced landfilling in favour of increased recycling of energy and materials lead to lower environmental impact, lower consumption of energy resources, and lower economic costs. Landfilling of energy-rich waste should be avoided as far as possible, partly because of its negative environmental impacts, but mainly because of the low recovery of resources of this option. In this way, Koroneos and Nanaki (2012) pointed out that environmental impacts are decreased when the solid waste management methods include some kind of recovery from waste. The results of their work indicate that paper recycling and anaerobic digestion of food waste is preferable compared to landfilling. Therefore, an integrated system which recovers nutrients, materials and energy from the waste stream, and reduces landfill disposal of organic and recyclable waste makes that GHG emissions decrease very significantly compared to conventional landfill disposal (Menikpura et al., 2013).

Another possible alternative to landfills is to apply thermal treatments to the MSW. Thermal treatment using incineration technology has been proven as an attractive method of waste disposal for many years due to the primary advantages of hygienic control, volume reduction, and energy recovery (Chang et al., 1998). But thermal treatments should not be detrimental to MSW recovery policies, such as reuse and recycling. Domestic and commercial waste must be treated with the aim of utilizing its energy content, while at the same time recycling as much of its material content as possible (Wittmaier et al., 2009). Therefore the

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MSW that has been collected must first be treated in an industrial plant such as a mechanical-biological treatment (MBT) plant. The main objective of this type of industrial plants is to reduce the content of waste biodegradable organic matter in order to minimize its environmental impacts when landfilled (odour production, self-heating and self-combusting, biogas production, leachate and pathogen growth) (Barrena et al., 2009). Another aim is to recover materials (biowaste is transformed into compost) to comply with the current legislation and to recover as much recyclable material as possible.

As a result of the treatment of MSW in a MBT plant, paper and cardboard, cardboard packaging, metal, plastics, glass and biowaste are separated from the residual fraction that cannot be exploited and that is finally dumped in a landfill. But this residual fraction, also called reject fraction (RF), can be profitable from the environmental and economic point of view. It can be turned into a refuse-derived fuel (RDF), which is waste that has been treated (or processed). This process consists in eliminating the non-combustible fraction, reducing its size and moisture content, homogenization of the waste, and in some cases its transformation into pellets.

The proper estimation of the energy content of the residual fraction from MBT plants is essential for planning and promoting different methods to decrease its environmental impact, to lower the consumption of energy resources, and to reduce economic costs (Aranda et al., 2012). In this way, Montejo et al. (2011) analyzed the material recovery carried out of 10 MBT plants in order to compare the efficiency of incineration of both fractions The RDF is traded and co-burnt in installations for power generation or in manufacturing processes where heat is required. RDF covers a wide range of waste materials which have been processed to comply with guidelines or regulatory or industry specifications mainly to achieve a high calorific value. The term RDF usually refers to the segregated high calorific fraction of processed MSW.

In the European Union, it is estimated that the total amount of RDF produced from MSW is about 4–5 million tonnes annually (Grau and Farré, 2011). This production capacity is being increased in many countries thanks to the implementation of new MBT plants. For example, in 2009, there were 120 material recovery and composting facilities in Spain (MMAMRM, 2010) and according to the Spanish Integrated National Waste Plan (PNIR) 2008–2015, an increase in the number of this kind of treatment facilities is foreseen.

The main advantages of using RDF as a fuel are an important reduction in the volume of waste and the possibility of energy recovery. Recognition of the integrated value of pre-sorting solid waste prior to the incineration process would offer a new perspective in solid waste management that includes the coordination of environmental benefits from solid waste pre-sorting, improved incinerator performance, and the direct revenues from recycled materials (Chang et al., 1998). Nowadays a number of industries are interested in this type of fuel. Many authors agree that the main potential RDF users are the cement and power industries, and industrial boilers (Nithikul et al., 2011). In countries like Germany, energy-intensive industries like cement, paper, chemical production or power generation would be interested in the use of RDF, either as co-combustion in modified existing plants or as mono-combustion in specifically designed boilers (Rotter et al., 2004). However, energy recovery from MSW is very controversial due to the atmospheric emissions (Genon and Brizio, 2008). Otherwise, nowadays the stringent requirements on air pollution can be controlled by using the existing technology correctly (Porteus, 2001). Some authors consider that the use of Solid Recovered Fuel (SRF) as co-fuel can reduce global warming and potential acidification significantly (Anurag et al., 2007).

The research work presented here is the result of the collaboration between the company Reciclados la Plana S.A (RECIPLASA) and INGRES, which is a research group at the Universitat Jaume I. RECIPLASA manages a MBT located in Onda (Spain). The main aim of this work is to analyse the possibilities of obtaining SRF from the RF in the mechanical selection stage and to define its physical and chemical properties. After the sampling process, the work has been structured in four sections. First of all, the physical and chemical properties of the waste reject fraction are determined. Second, the transformation and quality requirements to be met before RF can be used as a fuel are studied. Third, the legislation requirements in terms of energetic recovery are also presented. Finally, the effects of atmospheric emissions from using SRF are compared with the effects of other traditional fuels.

2. Materials and methods

As mentioned above, the RDF samples were taken from the MBT plant situated in Onda, a town in the province of Castellón, on the east coast of Spain. This plant treats the MSW collected from 25 municipalities with a total of approximately 400,000 inhabitants, which represents 464 t of MSW treated per day. The composition of the MSW treated in the plant is presented in Table 1.

According to the MSW management hierarchy, the aims of Onda's MBT plant are, on the one hand, to recover high quality materials and, on the other, to separate the biodegradable fraction. Using manual and mechanical processes, the MSW is divided into the main recovered fractions such as organic matter, paper, metals, plastics and bulky elements as showed in Fig. 1. Paper, plastic and bulky elements then undergo manual separation, the organic fraction is removed mechanically in a trommel and metals are removed by passing them through magnetic separators. After undergoing the correspondent treatments, paper and cardboard, metals and plastic are sent to another type of companies that process them or use them as raw material. The organic matter is separated and stabilized using biological treatments to produce compost. Finally, the RF is obtained downstream from the mechanical treatment process. The RF is formed by all the MSW materials that are not separated in the previous classification stages as they do not to satisfy the quality requirements to be recovered or recycled. At the MBT in Onda, it represents 43.10% of the initial mass of MSW treated and it is finally dumped on a landfill.

The experimental methodology is divided into three sections: collection of the RF sample, physical characterization of the RF sample, and chemical characterization of the RF sample.

2.1. Sampling process

The MBT plant in Onda generates 200 t of RF per day. This plant works six days a week, as there is no production on Sundays. The sampling process was carried out during the months of April, May and June (spring season). Some representative samples were taken in two non-consecutive weeks. The weeks were chosen taking into

Table 1
MSW composition at the MBT entrance.

MSW fraction	Percentage
Organic	57.1
Paper-card-board	15.2
Plastics	10.1
Glass	7.1
Metals	3.8
Textiles	3.5
Others	3.2

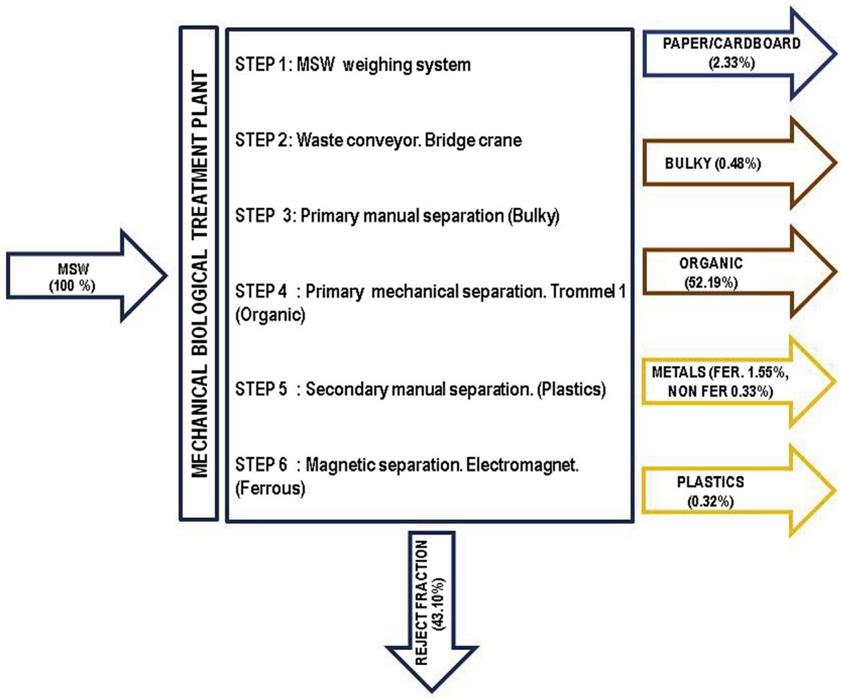

Fig. 1. Waste separation in Onda's MBT plant.

Table 2
Sample size reduction from five bales of RF.

Quarter number	0	1	2	3	4	5	6
Sample weight (kg)	8000	4000	2000	1000	500	250	125

account that there were no special events in them that could distort the results. Thus, twelve samples were taken, which correspond to 14 days' MSW generation.

In the Onda MBT plant, the RF is packaged in 1600 kg bales. It is calculated that between 125 and 130 bales are sent to the landfill every day. There was no information about the composition of the RF from the MBT plant in Onda from previous studies or from similar Spanish plants that could be used to calculate the number of bales needed to carry out the analysis. Hence, five bales were taken from the plant every day and analysed in the laboratory. The bales were collected at equidistant times throughout the working day. Therefore, 8000 kg of RF were used every day to extract the sample that would later be analysed in the laboratory. The bales were mixed in a sealed area and spread to form a circle which was divided into quarters. Two opposite sectors were taken and a new circle was formed with them. The new circle was again divided into quarters. The process was repeated until the sample mass was approximately 125 kg, as shown in Table 2.

2.2. Reject fraction physical characterization

The RF extracted at the plant was packaged in big-bags and taken to the laboratory. The big-bags were weighed and afterwards they were emptied onto the triage table. The manual selective triage of the RF makes it possible to know the physical composition of the RF based on mass percentages (Fig. 2), the size distribution, and the moisture content.

2.3. Reject fraction chemical characterization

Chemical characterization consists in defining the elemental components of the RF, which allows the different options for processing and recovering RF to be evaluated. Therefore, the sulphur (S), carbon (C), nitrogen (N), ash, heavy metals and halogens contents as well as the Net Calorific Value (NCV) were analysed. The S, C and N contents are especially important when applying thermal

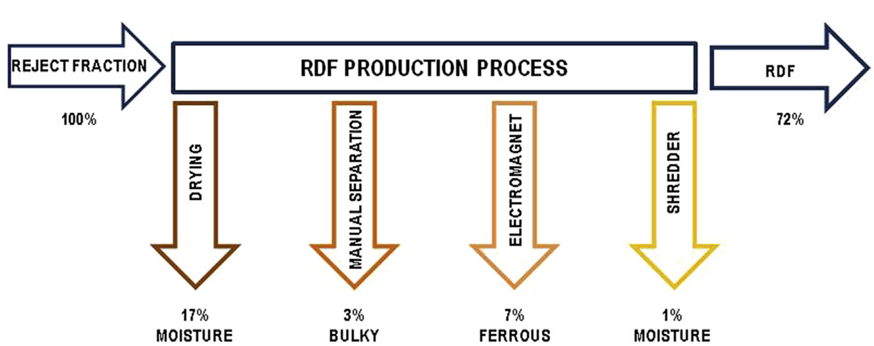

Fig. 2. RDF Production process in the laboratory.

Table 3
RF categories and composition.

Category		[a]WS average composition (%)	[a]WS standard deviation (%)	Moisture (%)	Moisture standard deviation (%)	[b]DS average composition (%)	[b]DS standard deviation (%)
Food and gardening waste		16.84	4.52	54.12	5.53	12.34	3.37
Sanitary cellulose		4.23	1.48	56.65	9.96	2.75	1.07
Paper and cardboard		32.15	3.72	41.64	4.67	28.64	3.88
Plastics	PET (1)	3.09	1.68	11.75	3.25	4.19	1.19
	HDPE (2)	2.40	1.30	6.46	1.31	3.38	0.85
	LDPE (4)	12.17	6.62	27.63	5.55	13.48	2.53
	PPc(5)	1.05	0.57	12.35	6.84	1.39	0.40
	PS (6)	1.01	0.55	18.38	4.28	1.25	0.38
	Others	2.47	1.34	9.04	6.54	3.46	1.79
Glass		1.13	0.59	1.43	0.71	1.71	0.90
Tetra Brick		2.03	1.12	29.40	3.82	2.19	1.20
Wood		3.25	1.42	31.27	6.99	3.34	1.29
Footwear		1.41	0.99	20.69	20.01	1.75	1.39
Textile		7.91	2.50	30.83	7.22	8.28	2.51
Rubber and leather		0.60	0.39	12.86	11.86	0.84	0.57
Metals	Ferrous	3.28	1.98	12.04	3.82	4.62	3.67
	Non-ferrous	0.81	0.49	15.20	8.26	0.92	0.75
	Aluminium Foil	0.30	0.18	28.67	5.46	0.28	0,19
Hazardous materials		0.15	0.10	14.56	7.26	0.20	0.14
Soil, ash and ceramics		1.42	0.78	11.03	7.99	1.86	0.83
Others		2.29	2.40	7.77	4.75	3.12	3.17

[a] WS refers to the wet sample.
[b] DS refers to the dry sample.

treatments to the RF due to the formation of SO_2, CO_2 and NO_x which cause photochemical smog and the greenhouse effect.

In order to determine the C, N and S percentages, homogeneous dry samples with a particle size less than 1 mm were prepared. C and S contents were analysed using the SC-144DR analyser. This analyser determines C and S contents as a result of combustion of the sample. The mass of the samples introduced in the analyser was 0.25 g–0.30 g. Three repetitions of each analysis were always made.

The SO_2 and CO_2 generated were determined using infrared spectrophotometry. The N content was also determined as a result of the combustion of the sample, but in this case the NO_x was reduced to N_2, and N_2 was measured in a thermal conductivity detector (TCD). The twelve samples of dry CF were extracted and the mean values and their variance were calculated as shown in Table 4. In order to do that, twelve samples were first prepared (the different materials found in the samples were mixed in their corresponding proportions). After preparing the samples, they were shredded in a mill in several different stages, until the grain size of the sample was 1 mm.

Heavy metals are inorganic chemical pollutants and can present an ionic or molecular form. As a result of normal human activity, heavy metals are present in many types of solid waste produced by the industrial sector and in a lower concentration in MSW. There are a great variety of heavy metals that can cause serious damage to human health and the environment due to their cumulative toxic properties. The European legislation on industrial emissions, Directive 2010/75/EU, states that it is important to control the concentrations of some metals such as Cadmium (Cd), Thallium (Tl), Antimony (Sb), Arsenic (As), Lead (Pb), Chromium (Cr), Cobalt (Co), Copper (Cu) Mercury (Hg), Manganese (Mn), Nickel (Ni) and Vanadium (V), as well as Hydrochloric and Hydrofluoric acids. Metal contents were measured using the Inductively Coupled Plasma Mass Spectrometry (ICP-Mass) technique.

Table 4
Percentage of S, C, N and ash in the combustible fraction and net and gross calorific value.

	Dry CF sample average	Dry CF sample standard deviation
S (%)	0.10	0.025
C (%)	54.87	2.62
N (%)	0.90	0.21
Ash (%)	10.69	2.07
Net calorific value ($MJ \cdot kg^{-1}$)	21.36	1.21
Gross calorific value ($MJ \cdot kg^{-1}$)	22.44	1.21

Some halogens are also controlled in the combustion processes because they are potential air pollutants and they can cause problems in the combustion chamber. For example, Chlorine produces the formation of deposits in the kiln and oxidation on the inner layer of the kiln (Öhman and Nordin, 1998). As set out in Directive 2010/75/EU, it is important to control Chlorine (Cl) and Fluorine (F). In this research work, halogens were determined using ion chromatography.

3. Results

This section collects the results obtained in this research work. In this way, the results of the physical and chemical RF characterization are presented as well as the metals and halogens contents. Finally the RDF quality standards have been determined and the atmospheric emissions have been outlined.

3.1. Results of the RF physical characterization

The selected materials in the RF were classified in the categories shown in Table 3. The composition and the moisture depend on the origin of the generation, so this characterization is very important to evaluate the possibilities of RF recovery.

The moisture content allows both the waste water mass and the waste dry matter mass to be calculated. The average moisture value for the 12 sampling days considered was 34.46% and the standard deviation was 3.25. The moisture content affects the calorific value, which makes it necessary to establish a previous thermal treatment. The moisture value was obtained according to CEN/TS 15414-3 (2011). Once the moisture value is known, it is simple to calculate the dry sample (DS) average composition from the Wet Sample (WS) average composition. All these values are summarized in Table 3.

From the composition point of view, first of all, food and gardening waste makes up the largest fraction of the RF, at 16.98%.

The trommel screen aperture diameter was 8 cm. It could be reduced improving the splitting open refuse bags techniques. Food and gardening and sanitary cellulose fractions contribute to increase the level of moisture in the sample. Therefore, they must be separated more efficiently to reduce the moisture. Second, paper and cardboard is the fraction with the highest mass percentage, 32.15%. This is due to the manual pre-sorting carried out in the plant, which simply recovers big boxes, and no other sorting exists to reduce this fraction downstream of the trommel. Paper and cardboard also have a high moisture content. The plastics fraction accounts for 22.2% of the RF composition. This is a fraction with a lower moisture content, 19.80%. Within the plastics fraction, Low Density Polyethylene (LDPE), the material used for film bags, has the highest moisture content, 27.63%, because after using these bags they are usually impregnated with liquid. The percentage of glass content in the RF is small compared to the other fractions. In this case the selective collection has allowed a great amount of this material to be recovered. The mass percentage of the metal fraction is 4.39% but it could be reduced by improving the electromagnet system as well as the Foucault separator. The moisture values of this fraction are so high due to the leachate in the aluminium foil and in the cans. The presence of hazardous materials such as batteries, cosmetics, inks and drugs in the RF (0.15% as shown in Table 3) is lower than in the Spanish MSW (approximately 0.8–1%) (Elías, 2004). The reason for the reduction in the amount of hazardous materials is that part of them has been previously separated out at the MBT plant with the plastic and metal fractions. The inert fraction is mainly composed of soil, ashes and ceramics. The total composition percentage of these materials in the RF that was analysed is 9.23% and its moisture content is very low, 11.03%. The last item in Table 2 is the term “Others”, which corresponds to waste that was not considered in the previous categories, such as electric and electronic waste, foam or products made of different materials. In order to use the RF as a fuel it must be considered a combination of combustible and non-combustible materials. The non-combustible fraction (NCF) consists of four categories: glass; metals; soil, ash and ceramics; and others. The combustible fraction (CF) is composed of the rest of the categories listed in Table 2. The CF represents a high percentage of the total RF – 90.70% considering the wet sample and 87.49% taking into account the dry sample. The NCF is a fraction that is easy to segregate from the RF simply by using mechanical treatments as sieves and densimetric tables.

3.2. Results of the RF chemical characterization

According to Table 4, the dry sample of CF presents a low value of S, 0.1%, which is even lower than the amount of S in the best quality coals, with a value of about 0.8–1%. The N content is also lower than that of coal. The composition and amount of ash depend on the incineration conditions. The percentage of ash makes it possible to know the amount of unburned product and therefore to foresee its management. Its composition and its quantity influence the combustion technology to be used, the characteristics of the kiln, the temperature and the extraction method (Tortosa et al., 2007). The methodology employed in this case is CEN/TS 15403 (2011). As shown in Table 3, the percentage of ash is about 10%, a reasonable value for this type of material. The Carbon, Hydrogen and Nitrogen content have been determined according to CEN/TS 15407 (2011).

On the one hand, the calorific value of the RF is essential to be able to evaluate the viability of using the RF as a fuel and to determine its energy efficiency. On the other hand, in many kilns, their design and control depend on the calorific value of the material used as fuel (Erol et al., 2010). The calorific value of waste is the energy released per unit mass or volume as a result of the combustion of the waste material in the presence of oxygen. In order to calculate the net calorific value, the water vaporization latent heat must be subtracted from the gross calorific value. The NCV of the combustible fraction was calculated in accordance with CEN/TS 15400 (2011) using a constant volume bomb calorimeter. The results presented in Table 3 show that the dry CF can be a good fuel compared to other types of fuels as the ones derived from coal anthracite or lignite (Spanish inventory of greenhouse gasses emissions, 2011).

Heavy metal and halogen contents are more difficult to calculate due to the low concentrations and the heterogeneity of the sample. These facts are reflected in the high values of the standard deviation. As shown in Table 5, Mn, Cr and Cu are the metals with the highest presence. The high Cr content is due to the tanning industry present in the zone, while the high Cl level is due to plastic packaging.

3.3. Results of the RDF quality standards

The main application of the CF of the RF is its utilization as a fuel in the industrial and energy sectors. The discussion about characteristics and quality standards associated with waste processing for fuel production is led by three participating groups: the RDF producers, potential RDF customers, and the respective authorities. Furthermore, the RDF production must take into account some basic rules. It must ensure the protection of the combustion facilities as well as the industry final product. To decide whether the RDF created from the RF of MSW treatment plants can be used as a fuel in the different technologies currently in use, it is necessary to know its physical and chemical characteristics as well as its thermal behaviour (Kaliyan and Morey, 2009). Moreover, the energetic and mineral RDF content must be stable enough to allow optimal operation in industry. The physical state of the RDF must allow safe handling and storage and, above all, the chemical and physical quality of the RDF must satisfy environmental specifications. In order to ensure a predefined quality, the RDF is subject to standards. Therefore some countries like Germany, Italy or Finland have defined their own quality standards for this type of products. In Germany the control of RDF manufacturing was verified by means of RAL-GZ 724 (2012) where average and percentile limit values of 80% were defined. In Italy, the UNI 9903 (2004) regulation sets the medium physical–chemical properties of RDF. In Finland, SFS 15358 (2011) has defined three quality levels for each parameter, Class I being the most stringent, and it also sets out the characteristics of the production process. Other countries like Spain, Switzerland or UK have defined specific quality standards covering

Table 5
Heavy metal and halogen contents in the combustible fraction.

Heavy metal or halogen	Dry CF sample average ($mg \cdot kg^{-1}$)	Dry CF sample standard deviation ($mg \cdot kg^{-1}$)
V	5.95	4.22
Cr	135.49	98.7
Mn	136.27	91.25
Co	4.63	2.28
Ni	19.92	9.95
Cu	108.92	45.21
As	21.41	13.63
Cd	9.80	7.15
Sb	55.85	27.20
Hg	82.66	29.97
Tl	1.33	1.23
Pb	63.86	27.64
Cl	3359.25	509
F	62.20	56.17

Table 6
RDF quality standards.

Parameters	Unit	Dry CF	General standards		Cement kiln standards		
			Italy	Finland quality I	Spain	EURITS	Switzerland
Moisture	%	0	<25		< 1		< 10
Net Calorific Value	MJ·kg^{-1}	20.6	15			15	25.1–31.4
Ash content	%	10.69	20		<< 10	5	0.6–0.8
Cl	%	0.335	0.9	<0.15		0.5	<1
S	%	0.103	0.6	<0.20	<3	0.4	<0.5
N	%	0.901		<1.0	<3	0.7	
F	%	0.0062				0.1	
K, Na	%			<0.20			
Hg	mg·kg^{-1}	82.66		<0.1			<5
Cd	mg·kg^{-1}	9.80		<1.0			<5
Pb	mg·kg^{-1}	63.86	200		<2.500		<100
Cu	mg·kg^{-1}	108.92	300				
Mn	mg·kg^{-1}	136.27	400				
Cr	mg·kg^{-1}	135.49	100		<1.500		<30
Zn	mg·kg^{-1}		500			500	<2000
Ni	mg·kg^{-1}	19.92	40				<10
As	mg·kg^{-1}	21.411	9				
Ba	mg·kg^{-1}				<5.000		
Cd + Hg	mg·kg^{-1}	92.46	7				
Br/I	mg·kg^{-1}					0.01	
Hg/Ti	mg·kg^{-1}					2	
As, Se (Te), Cd, Sb	mg·kg^{-1}	87.06				10	
Mo	mg·kg^{-1}					20	
V, Cr, Co, Ni, Cu, Pb, Mn, Sn	mg·kg^{-1}	475.04				200	
V	mg·kg^{-1}	5.95					<50
Zr	mg·kg^{-1}						<300
Halogens	%	0.34			<5		

the use of the RDF in cement kilns in order to adapt it to the process correctly. The European Association of Waste Thermal Treatment Companies for Specialised Waste (EURITS, 1996) has published criteria for waste co-incinerated in cement plants as a substitute fuel that countries like Belgium are currently using. Otherwise, an experimental technique determined the emissions of various pollutants (PAHs, PCDD/Fs, metals, acid gases, etc.) in a cement kiln fed with different proportions of RDF from MSW. It showed that in the cement kiln, pollutants concentrations were under the legal limits. In this case, no correlations were found between the different RDF proportions and metals emissions (Conesa et al., 2011).

Table 6 shows some of these quality standards and the Onda plant's parameters so that they can be compared. Results in Table 6 show that the CF satisfies the NCV standard quality requirements (except for Switzerland), so it could be used as a fuel without any problems. The ash content only satisfies the Italian requirements, so this parameter should be improved. Regarding Cl and F, the dry CF has a very low percentage of them, so it satisfies almost all the regulations considered in this work. It also satisfies S and N limit contents (except EURITS limits, in the case of N). In contrast, not all the heavy metals satisfy the preset requirements from the different regulations. Regarding the quality standards of the Spanish cement kiln, except for the ash content, it satisfies all the limit parameters. Nevertheless, the ash percentage could easily be reduced if the inert material (dust and dirt) that covers all the materials that form the RF were previously eliminated by some mechanical treatment such as sieving.

In Europe, the CEN (European Committee for Standardization) published the standard reference EN 15359 (2011) that establishes standards and technical specifications for SRF for European markets. In this regulation the SRF is defined as combustible obtained from non hazardous waste. It is important to distinguish SRF from RDF as a SRF is only made of non hazardous waste while a RDF is made of any type of waste, hazardous and non hazardous waste. In order to commercialise the SRF, it must be previously classified according to the NCV because it assesses the economic aspects, the Cl content that evaluates the technological constraints and the Hg content to calculate the environmental impact. All these values are estimated as defined in CEN/TS 15359 (2011).

According to the results shown in Table 7, the RDF from the CF of the Onda MBT RF can be considered an SRF. The class code of Onda's SRF with a mean Net Calorific Value of 20.6 MJ/kg, a mean chlorine content of 0.33% and a median mercury content of 4 mg/MJ is classified as NCV 2; Cl 2; Hg 5. All the parameters have acceptable values except for Hg, which should be improved to satisfy the European Norm EN15359:2011.

3.4. Results of the atmospheric emissions

Directive 2003/87/EC establishes a scheme for greenhouse gas emission allowance in order to promote its reduction in a cost-effective and economically efficient manner. This directive specifies a series of actions to reduce greenhouse emissions. It focuses on the reduction of the anthropogenic emissions of greenhouse gases by 8%, as compared to the levels in 1990, over the period 2008 to 2012. The Directive-specified installations must hold a gas emission permit issued by a competent Authority. The Directive establishes that if an installation uses fuels containing biomass, the emissions produced by that fuel combustion are not declared as CO_2 emissions.

Table 7
EN 15359 classes classification.

Classification property	Statistics measure	EN 15359 classes					
		1	2	3	4	5	Dry CF
Net Calorific Value (MJ·kg^{-1})	Average	≥25	≥20	≥15	≥ 10	≥3	20.6
Cl (%)	Average	≤0.2	≤0.6	≤1.0	≤1.5	≤3.0	0.335
Hg (mg·MJ^{-1})	Median	≤0.02	≤0.03	≤0.08	≤0.15	≤0.50	4.06
	80% percentile	≤0.04	≤0.06	≤0.16	≤0.30	≤1.00	4.59

Table 8
Comparison of atmospheric emissions, in $m^3\ MJ^{-1}$, using conventional fuels and the dry CF (Volume measured in normal conditions).

	Anthracite	Lignite	DryCF
CO_2	0.8890	0.8210	0.8420
SO_2	0.0029	0.0075	0.0004

In the Onda CF, biomass is made up of food and gardening waste and wood, which represent 20.09% of the total CF (taking into account the wet sample).

The flue gas volume and composition were calculated from the chemical composition of the RF and assuming that the controlled combustion was carried out under stoichiometric conditions. Table 8 shows the flue gas CO_2 and SO_2 emission per calorific unit. Calculations were performed taking into account the fact that the NCV of anthracite, lignite and the RF are 16.94 $MJ\ kg^{-1}$, 16.0 $MJ\ kg^{-1}$ and 21.34 $MJ\ kg^{-1}$ respectively.

The CO_2 emissions due to CF combustion must be calculated according to Eq (1) and the subtraction corresponding to biomass combustion must be taken into account. Therefore the CF combustion really generates 0.6908 $m^3\ MJ^{-1}$, a value lower than the one shown in Table 7. Thus, from the point of view of CO_2 and SO_2 emissions, the SRF obtained from the dry CF presents better results than anthracite and lignite.

4. Conclusions

The main conclusion of this research work is that the RF produced in the mechanical separation of a MBT plant can be transformed into a fuel which can be used for energy generation, thereby notably reducing the amount of MSW sent to a landfill.

Relying on the results of the characterization of the spring season RF, it is proved that the plant in Onda can reduce its current RF from 43.10% to 1.63% if it is processed and transformed into SRF. From the total wet sample RF, 90.70% is combustible material and 5.52% is non-combustible recyclable material (glass and metal), so there is only 3.78% of material that cannot be put to any use.

The SRF thus obtained has some characteristics that make it adequate for use as co-combustible in cement kilns. Its physical composition has significant share of biodegradable organic matter (20.09%), although this percentage can be reduced by increasing the separation efficiency; nevertheless, from the point of view of CO_2 emissions, this fraction of material is not taken into account. The paper and cardboard fraction is largest and has a higher percentage of moisture. If this fraction separation efficiency increases, the percentage of recyclable materials will be raised and the RF moisture will be decreased.

Regarding the chemical composition of the SRF, it can be said that it satisfies most of the parameters set by different organizations and especially the Spanish Cement Kilns Standard. The ash content is one of the most important parameters. In this case, the SRF exceeds the limits. Nevertheless, it could be improved using mechanical treatments.

The new European regulations on RDF introduce the term SRF and a classification process based on some quality parameters. Onda's SRF is classified as NCV 2; Cl 2; Hg 5, having all the parameters acceptable values except for Hg, which should be improved to satisfy the European Norm EN15359:2011.

Further research should be carried out to find out the origin of this high concentration. Finally, according to CO_2 and SO_2 emissions, the SRF presents better results than anthracite and lignite.

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References

Anurag, G., Smith, R., Hill, D., 2007. Wastes as co-fuels: the policy framework for solid recovered fuel (SRF) in Europe, with UK implications. Environ. Sci. Technol. 41, 4868–4874.
Arafat, H.A., Jijakli, K., Ahsan, A., 2013. Environmental performance and energy recovery potential of five processes for municipal solid waste treatment. J. Clean. Prod. http://dx.doi.org/10.1016/j.jclepro.2013.11.071.
Aranda, A., Ferreira, G., Zambrana, D., Zabalza, I., Llera, E., 2012. Estimation of the energy content of the residual fraction refused by MBT plants: a case study in Zaragoza's MBT plant. J. Clean. Prod. 20, 38–46.
Barrena, R., d'Imporzano, G., Ponsá, S., Gea, T., Artola, A., Vázquez, F., Sánchez, A., Adani, F., 2009. In search of a reliable technique for the determination of the biological stability of the organic matter in the mechanical-biological treated waste. J. Hazard. Mater. 162, 1065–1072.
CEN/TS 15359, 2011. Solid Recovered Fuels. Specifications and Classes.
CEN/TS 15400, 2011. Solid Recovered Fuels. Methods for the Determination of Calorific Value.
CEN/TS 15403, 2011. Solid Recovered Fuels. Methods for the Determination of Ash Content.
CEN/TS 15407, 2011. Solid Recovered Fuels. Methods for the Determination of Carbon (C), Hydrogen (H) and Nitrogen (N) Content.
CEN/TS 15414–3, 2011. Solid Recovered Fuels – Determination of Moisture Content Using the Oven Dry Method – Part 3: Moisture in General Analysis Sample.
Chang, W.C., Chen, Y., Chang, N., 1998. Comparative evaluation of RDF and MSW incineration. J. Hazard. Mater. 58, 33–45.
Conesa, J.A., Rey, L., Egea, S., 2011. Pollutant formation and emissions from cement Kiln Stack using a solid recovered fuel from municipal solid waste. Environ. Sci. Technol. 45, 5878–5884.
Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emissions allowance trading within the Community and amending Council Directive 96/61/EC.
Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control).
Elías, X., 2004. Hazardous waste presence in the MSW conditions its management. Residuos 81, 34–49.
Eriksson, O., Reich, M.C., Frostell, B., Björklund, A., Assefa, G., Sundqvist, J.O., Granath, J., Baky, A., Thyselius, L., 2005. Municipal solid waste management from a systems perspective. J. Clean. Prod. 13, 241–252.
Erol, M., Haykiri-Acma, H., Küçükbayrak, S., 2010. Calorific value estimation of biomass from their proximate analyses data. Renew. Energ. 35, 170–173.
European Association of Waste Thermal Treatment Companies for Specialised, 1996. EURITS Criteria for Waste Co-incinerated in Cement Plants.
Finnveden, G., Johansson, J., Lind, P., Moberg, A., 2005. Life cycle assessment of energy from solid waste – part 1: general methodology and results. J. Clean. Prod. 13 (3), 213–229.
Genon, G., Brizio, E., 2008. Perspectives and limits for cement kilns as a destination for RDF. Waste Manage. 28, 2375–2385.
Grau, A., Farré, O., 2011. Situation and Potential of the Direct Waste Energy Recovery. Technical study. PER 2011–2020. IDAE.
Kaliyan, N., Morey, R.V., 2009. Factors affecting strength and durability of densified biomass products. Biomass Bioenerg. 33, 337–359.
Koroneos, C.J., Nanaki, E.A., 2012. Integrated solid waste management and energy production – a life cycle assessment approach: the case study of the city of Thessaloniki. J. Clean. Prod. 27, 141–150.
MAGRAMA, 2010. Spanish Ministry of Agriculture, Food and Environment. Anual Statistics Report. Madrid.
Menikpura, S.N.M., Sang-Arun, J., Bengtsson, M.J., 2013. Integrated solid waste management: an approach for enhancing climate co-benefits through resource recovery. J. Clean. Prod. 58 (1), 34–42.
Montejo, C., Costa, C., Ramos, P., Márquez, M.C., 2011. Analysis and comparison of municipal solid waste and reject fraction as fuels for incineration plants. Appl. Therm. Eng. 3, 2135–2140.
Murphy, J.D., McKeogh, E., 2004. Technical, economic and environmental analysis of energy production from municipal solid waste. Renew. Energ. 29, 1043–1057.
Nithikul, J., Karthikeyan, O., Visvanathan, C., 2011. Reject management from a mechanical, biological treatment plant in Bangkok, Thailand. Resour. Conserv. Recy. 55, 417–422.
Öhman, M., Nordin, A., 1998. A new method for quantification of fluidized bed agglomeration tendencies: a sensitivity analysis. Energ. Fuel 12, 90–94.
Porteous, A., 2011. Energy from waste incineration – a state of the art emissions review with an emphasis on public acceptability. Appl. Energ. 70, 157–167.
Rotter, V.S., Kost, T., Winkler, J., Bilitewski, B., 2004. Material flow analysis of RDF-production processes. Waste Manage. 24, 1005–1021.
RAL-GZ 724:2012-01. Quality and Text Instructions Solid Recovered Fuel.

SFS-EN15358, 2011. Solid Recovered Fuels. Quality Management Systems. Particular Requirements for Their Application to the Production of Solid Recovered Fuels.
Spanish Inventory of Greenhouse Gases Emissions, 1990-2009. Ministry of Environment, Madrid. Spain.
Tortosa Masiá, A.A., Buhre, B.J.P., Gupta, R., Wall, T.F., 2007. Characterising ash of biomass and waste. Fuel Process. Technol. 88, 1071–1081.
UNI 9903–1, 2004. Non Mineral Refuse Derived Fuels – Specifications and Classification.
Wittmaier, M., Langer, S., Sawilla, B., 2009. Possibilities and limitations of life cycle assessment (LCA) in the development of waste utilization systems – applied examples for a region in Northern Germany. Waste Manage. 29, 1732–1738.