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Environmental impact of rejected materials generated in Organic Fraction of Municipal Solid Waste anaerobic digestion plants: comparison of wet and dry process layout

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1. Introduction

Municipal Solid Waste (MSW) management systems are being implemented in most of the countries all over the world. European Union (EU) countries have a wide experience in the implementation of different management systems, including waste collecting and treatment. EU has promoted some Directives pointing to reduce MSW generation, increase recycling, promote source selection and reduce biodegradable wastes to landfilling. For example, EU published in 1999 the Landfill Directive (European Commission, 1999), through which all its State Members are required to minimize landfill disposal and are encouraged to adopt more sustainable measures, with the objective to reduce the environmental impact of landfills. Later, the EU waste policy, Framework Directive (2008/98/CE), required all its State Members to apply the waste hierarchy concept. Waste management options are classified according to their environmental impact into five categories (most favoured options first): Prevention, Reuse, Recycling, Recovery and Disposal. As a consequence, now-a-days, EU municipal solid waste is disposed through landfill (33.6%), incineration (24.2%), recycling (27.4%) and composting and anaerobic digestion (14.8%) (Eurostat, 2012).

Probably, the Landfill Directive is the main responsible of the increasing number of Mechanical Biological Treatment (MBT) Plants in Europe. Indeed, while in 1990 the annual treatment capacity was around 0.1 million t/y, by 2010 in Europe, there were around 200 plants with a total treatment capacity of 6 millions t/y spread in 17 EU countries (De Baere and Mattheeuws, 2010). However, there is growing interest in the diversion of food waste from landfills in other countries such United States or Canada (Levis et al., 2010).

MBT plants are based on three main stages. A first mechanical stage aiming to, by one hand, recyclables (ferric and non-ferric metals, plastics…) and, by the other hand, the organic (biodegradable) fraction. Recyclable material are sold and reused as raw materials. The organic fraction undergoes to a second stage based on a biological degradation process. Anaerobic digestion followed by a composting process or only composting of the organic fraction are the main used options for the material valorisation of the organic fraction. Finally, the raw compost is refined through mechanical processes. Biogas (from the anaerobic digestion process) compost and reciclables are thus obtained as final products in MBT plants.

Anaerobic digestion processes can be defined as wet or dry anaerobic digestion. Wet anaerobic digestion is defined when waste to treat is digested at less than 20% dry solids. While, dry anaerobic digestion processes, are considered when wastes with higher dry solids content are digested and, when working at the boundary, the process is called semi-dry anaerobic digestion (Hartmann and Ahring, 2006). Depending on the type, wet or dry, the initial mechanical stage will be different. Both cases comprise a dry mechanical treatment (trommel, ballistic separation, magnetic separation…), but wet anaerobic processes require also a previous wet treatment. The objective of this wet treatment is to increase water content, to remove light fraction (low-density material such plastics or fibers) and to remove high-density materials (such as sands).

MBT plants can treat mixed MSW or source selected Organic Fraction of MSW (OFMSW). In both cases, the three stages mentioned above will be necessary (mechanical, biological and refining stage). During these stages, mainly the first mechanical stage, some refuses are generated. Refuse will be constituted by materials that cannot be clearly separated as recyclables or as biodegradable fraction and are normally landfilled or, in some cases, used as Refuse derived fuel (RDF). In an OFMSW MBT plant, refuse is related with the non-biodegradable materials present in the waste (plastics, metals, sand, etc.). Quantity of undesirable wastes in the OFMSW is related with some socio-economic factors: population density, Gross Disposable Household Income, educational level or the collection system (street bins o door to door) (Alvarez et al., 2007).

Since mechanical selection (dry and wet) is not 100% efficient, refuse fraction will content organic biodegradable matter among other recyclables. Thus, some of the biodegradable matter that should be valorised through the biological stage is send to landfill, with the consequent economic and environmental impacts: less biogas and compost are produced and there will be an increase in landfill emissions.

Landfills are responsible for a considerable contribution to several environmental burdens, being one of them the Global Warming, that is caused by increasing amounts of greenhouse gases (CO_2, CH_4, N_2O…) being emitted to the atmosphere. Among these, methane emissions are a major contribution since it is 34 times more harmful than the same volume of carbon dioxide (IPCC, 2013). Landfills remain one of the main sources of methane emissions, because most of the methane gas produced leaks into the atmosphere. In Europe, it is estimated that approximately 60% of landfill biogas (LFG) is lost to the environment (Cherubini et al., 2009, Buttol et al., 2007, Monni, 2012).

In this context, it becomes essential to evaluate the environmental impact associated with MBT treatment facilities. Some studies have assessed the sustainability of the process itself (Colón et al., 2012, Cadena et al., 2009, Montejo et al., 2013). Other studies have studied the input and output flows of MBT plants and the mass balance (Pognani et al., 2012) including the refuse produced in MBT plants. However, no data has been found in literature about the environmental impact of the refuses generated by full-scale OFMSW treatment plants that have landfill destination. Environmental impact of complex systems can be addressed by means of Life Cycle Assessment (LCA). LCA is a methodological tool for studying the environmental aspects and potential impacts of a product or service throughout its lifecycle, from extraction of raw materials, production, its use and finally, its disposal. An LCA involves the development of relevant information on inputs and outputs of the system (inventory analysis), the assessment of their potential impact (impact assessment) and the interpretation of the results within the context of proposed targets (interpretation) (ISO 14040, 2006). Simply stated, LCA performs mass and energy balances of a product system, and makes an assessment of the environmental impacts associated to them.

The main goal of this study is to evaluate the environmental impact of MBT refuses from two full-scale anaerobic digestion plants, focusing on potential methane emissions. Selected MBT plants comprise dry and wet anaerobic digestion processes. Characterization of the refuses and by means of Biochemical Methane Potential test and evaluation of the biogas loss derived from landfilling the organic content of the refuse streams are included. Finally, LCA is used as a complementary tool to determine and compare the environmental impact of the wastes generated by each OFMSW full-scale plant analysed.

2. Materials and Methods

2.1. Plant description

Two different Anaerobic digestion facilities were studied, the first one relying on a wet anaerobic process (BTA® technologies) and the second one relying on a dry anaerobic process (Valorga® technologies).

2.1.1. Wet Anaerobic Digestion plant

This is a medium-scale wet anaerobic digestion plant located in Catalonia, Spain. The plant treats 45,000 tons of source-selected OFMSW and produces 4,275,000 Nm^3 of biogas per year.

Accepted, material is discharged in a warehouse with total capacity 2.5 times bigger than its daily capacity. Waste is feed then to the Dry pre-treatment. First operation consists of a bag opener machine. Afterwards, OFMSW is fed into a 100 mm trommel screen that splits it into two fractions: an oversized fraction (Dp>100 mm) that is sent to landfill and an undersized fraction (0<Dp<100 mm) that goes into further pre-treatment stages.

The next step is a magnetic separator where ferrous metals are removed and sent to recycling and reuse. The remaining material goes through a pneumatic aspiration system that captures light plastics and improper materials such as low-density polyethylene (LDPE), polystyrene, small high-density polyethylene packaging and other small plastic items. Other improper materials separated in this stage are bones, sands, olive pits and small-sized pieces of glass.

Furthermore, rolling materials are separated using a ballistic separator, after which the remaining fraction enters a 15 mm vibrating screen that removes particles with granulometry between 0 and 15 mm. The remaining material with particle diameter between 15 and 100 mm enters Wet pre-treatment which includes 2 pulpers, with the main purpose of preparing a suspension of the organic fraction with the right content of total solids, by mixing waste with process water. Pulpers also remove heavy and light impurities. On one hand, non-organic materials (plastic, textiles, bones) are not affected by agitators and are more likely to be deposited on the bottom of the tanks, which is equipped with a screw for their extraction. On the other hand, light materials float and are captured by the hydraulic extraction system. Both refuses are stored in containers and sent to landfill.

Finally, the pulp is fed to a hydrocyclone that separates heavy, inert material with Dp<10 mm that may still be suspended. This material is sent to landfill together with the heavy fraction from the pulpers. The cleaned suspension is stored in a tank before entering the digesters, in order to provide them a continuous feed. The plant is equipped with two anaerobic digesters of 3,000 m^3 capacity that work under mesophilic conditions and in a single –stage process.

The digested suspension is pumped into the dehydrating system that is formed by two centrifuges that split it into two fractions: a liquid and a solid one. The latter has a dry matter content between 26-28 % and is sent to the composting tunnels to mature while water is recirculated to the pulpers. A flocculating polyelectrolyte is added in order to improve the separation. The liquid fraction is partially recirculated to the pulpers and the rest is sent to a wastewater treatment plant. The digestate is mixed with pruning waste, used as bulking agent, in a 2:1 ratio (in volume), two parts of digestate per part of pruning waste.

After composting has been completed, mature compost is refined with the aim to remove improper material that may affect its final quality as well as its aspect and commercial value. Compost is sent to a 10-15 mm densimetric table that removes glass and stones and separates two fractions: Dp>10-15mm is recirculated and used as bulking agent and Dp<10-15 mm is final compost.

2.1.2. Dry anaerobic digestion plant

This is a dry anaerobic digestion plant located in Catalonia, Spain. The plant consists of two separated production lines: one for source-selected OFMSW and one for mixed residual waste. Data collected in this work belongs exclusively to the OFMSW line. The plant treats 95,000 tons of source-selected OFMSW and produces nearly 8,640,000 Nm^3 of biogas per year.

The first pre-treatment stage consists of manual separation of glass, voluminous and other improper materials that may be present. Adequate material is grinded and then screened in an 80 mm trommel. Particles with Dp<80 mm are fed to a magnetic separator where ferrous metals are removed and sent to recycling and reuse.

Before entering the anaerobic digester, the remaining waste is homogenized, diluted and heated in a mixer in order to achieve optimum conditions for microbial degradation. Dilution and homogenization are accomplished by recirculating digested material, whereas heating is assured by injecting water vapor to the system just before entering the digesters.

Remaining organic material is anaerobically digested in a 4,500 m^3 digester. The plant uses the *Valorga* system, in which organic matter is processed via dry anaerobic digestion and in mesophilic conditions.

Digested material that is not recirculated enters the dehydrating system. It enters a 3 mm dewatering screw press that separates two phases: a solid with 54% DM that goes to composting and a liquid with 12% DM that is subject to further dehydrating. It is fed to a centrifuge where a solid with 25% DM is obtained and sent to composting. The remaining liquid has a 4 % DM and is sent to the wastewater treatment plant. Polyelectrolyte is added in order to aid flocculation.

In order to obtain an organic amendment with the appropriate granulometry and improper content, the composted material needs to be refined. The first equipment in this line is a 20 mm trommel screen. Oversized material is rejected and the undersized particles are fed to a densimetric table that separates heavy items such as glass and rocks. Finally, the remaining stream is screened in a 10 mm trommel and material with Dp<10 mm is considered compost.

2.2. Sampling, processing and characterization

Different sampling methodologies were applied depending on the characteristics of the material to be analyzed. In the case of continuous flows (conveyor belts), a subsample of around 3-4 kg was taken every 5 minutes, to finally obtain a sample of 15-20 kg. When samples were obtained from piles, 3-4 kg was taken from different points of the pile to finally obtain a sample of 15-20 kg.

In the case of dry pre-treatment samples, a subsample of approximately 10 kg was wet-crushed to Dp<15mm in an organic household waste grinding machine.

All samples were frozen within 12 hours after sampling at temperatures between -18°C and -20°C. Thawing of the samples lasted no longer than 24 hours at room temperature but never exceeding 25°C. Sample preparation must be completed and tests started within 14 days after sampling

Dry pre-treatment samples received a further characterization. Approximately 10 kg of subsample where classified into different materials. The categories used were: glass, organic, textile, plastic, metal, paper, mineral and wood.

2.3. Analytical methods

2.3.1. Physico-chemical parameters

Dry matter (DM), moisture content (MC) and volatile solids (VS) were determined according to the standard procedure outlined in *Test Methods for the Examination of Composting and Compost* (TMECC) (US Department of Agriculture and US Compost Council, 2001).

2.3.2. Biomethane potential test

The biogas potential and methane production from samples were determined using the procedure described by Ponsá et al. (2011). Briefly, the sample was mixed with an anaerobic inoculum in sealed aluminium bottles of 1 liter working volume. The mixture is made in the bottle by adding the correspondent amounts of inoculum and sample to finally obtain 600 ml of mixture and around 400 ml of headspace in the bottle. When making the mixtures inoculum-sample, the organic load was carefully take into account. This is necessary since medium acidification and inhibition of microorganisms by volatile fatty acids accumulation may occur if the content of easily hydrolysable organic matter in the sample is excessive. Therefore, different inoculum:sample ratios were used to carry out the experiments, since all sample have different composition characteristics. The inoculum:substrate ratio in volatile solids basis ranged from 1:1 to 1:4, depending on the sample.

The bottles were incubated in a temperature controlled room at 37°C. The biogas generated was measured periodically. Before sealing each bottle, they were purged with nitrogen gas to ensure anaerobic conditions. The tests were carried out in triplicate and the results were expressed as biogas volume produced at normal conditions (in NL at T = 273 K, P = 1 bar) per kg of TS. A triplicate measure of the biogas production of the inoculum was carried out as a control and subtracted from the biogas production obtained with the faecal waste samples. A control test was conducted to verify that the inoculum had adequate biological activity according to the German Institute for Standardization. This tests states that biogas production should be at least 0.4 L_{biogas} $kg^{-1}{}_{TS}$ to validate the activity of the anaerobic inoculum used, which was the case here.

Total ultimate biogas or methane potential cannot be achieved in 21 days for OFMSW and MSW samples and longer tests need to be conducted in order to reach non-significant biogas production. In order to obtain these parameters, correlations suggested by Ponsá et al. (2011) were used to calculate GB100 (biogas potential at 100 days) from the experimental GB21 values obtained.

Biogas composition was analyzed by using a gas chromatograph Hewlett Packard 5890A GC (Agilent Technologies) equipped with a Thermal Conductivity Detector and a Porapak Q, 3m x 1/8''x 2.1mm (ID) 100/120 (Supelco) column. Analysis conditions were: helium as carrier gas at 340 kPa splitless, injector temperature at 150°C, detector temperature at 180°C, oven temperature at 70°C isothermal, injection volume was 100 µl.

2.4. Life Cycle Assessment

SimaPro® 7.3.3, by PRé Consultants, was the software used to evaluate the environmental impact potentials using the ReCiPe (H) mid-point method for all impact categories studied (Goedkoop et al., 2009). This analytical tool is in accordance with ISO 14040 standards (ISO 14040, 2006).

The environmental impact categories considered in all case studies were: Climate change (CC), Ozone depletion (OD), Terrestrial acidification (TA), Photochemical oxidant formation (POF), Freshwater eutrophication (FE), Fossil depletion (FD).

2.4.1. Goal and scope

The main goal of this study is to compare two different anaerobic digestion facilities, focusing on their refuse generation, in order to determine which technology has the best environmental performance, as well as identifying the critical points of each system with the objective of suggesting possible improvements.

The functional unit chosen was landfilling of refuses generated by processing 1 ton of OFMSW, considering a 100-year time horizon. This reference flow allows the comparison of the two systems independently of the plant capacity.

The system boundaries limit to the refuse generated by each plant and its subsequent landfilling, excluding its transportation to landfill site. Figure 1 describes the cut-off criteria applied to the system under study and delineates the system boundaries.

The landfill technology chosen to model the system is a sanitary landfill that uses bottom liner, top soil cover and gas and leachate collection and treatment systems. Gas collection efficiency is assumed to be 40%, corresponding to typical values found in literature (Manfredi and Christensen, 2009; Buttol et al., 2007; Monni, 2012; Obersteiner et al., 2007).

All collected gas is converted to electricity, with an efficiency of 25% as reported by several authors (Banar et al., 2009; Gentil et al., 2010; Cherubini et al., 2009).

2.4.2. Inventory analysis

Data required to perform the LCA comes from different sources. Firstly, plant production and refuse generation from each facility were supplied by plant managers. Plant data include: treatment capacity (tons of OFMSW treated/year), annual biogas production (Nm^3/year) and refuse generation, given individually per industrial refuse produced (tons/year).

In the case of refuses from wet-pretreatment and compost refuse, total refuse mass was divided into: inert material and biowaste. Inert material was considered to have 0% water content; so all water mass of the sample was attributed to biowaste. This division was made according to MC and VS parameters obtained for each refuse.

In the case of dry-pretreatment refuses, a deeper characterization could be sustained. Total refuse mass was divided into: textile (0% water), paper (11.2% water), plastics (15.3% water), inert material (0% water), wood (20% water), metal (0% water) and biowaste. Remaining water content of the sample was attributed to biowaste. Glass and mineral fractions of waste were considered inert material. Water contents of each material were selected to be in accordance with their corresponding the process reported in the Ecoinvent 2.0 and ELDC databases.

In terms of gaseous emissions, the biogas potential of each refuse was experimentally measured as explained above. Emissions of biogenic CO_2 were considered neutral to global warming because they result from the decomposition of organic material, as suggested by IPCC (2006). Methane emissions were determined according to biogas potential test and biogas composition. Methane emissions were allocated entirely to the organic fraction of the sample, except if paper and wood fractions were present. In this case, the methane emissions of paper and/or wood from the databases were subtracted.

Electricity generation was calculated according to the amount of methane present in the collected fraction of landfill biogas. Biogas was used entirely for electricity conversion purposes with an electricity conversion efficiency of 25% (Banar et al., 2009; Gentil et al., 2010; Cherubini et al., 2009).

For the landfill phase of the analysis, the processes from Ecoinvent v2.2 and the European Centre for Leadership Development (ELCD) database were used. Methane emissions and energy-avoided impacts were replaced by their corresponding experimental values.

2.4.3. Life Cycle Impact Assessment

To evaluate the environmental performance of the plant, the method used was ReCiPe Midpoint (H) v1.06 (World). This method considers a 100-year time horizon for the studied categories.

3. Results

3.1. Refuse characterization

Table 1 shows the amount and the physico-chemical properties of refuses streams produced at both wet and dry anaerobic digestion facilities. The dry pretreatment generates a fairly constant amount of refuses per ton of OFMSW ranging from 0.15 to 0.16 t refuse/t OFMSW. Moreover, in wet AD facilities, wet pretreatment (pulpers and hydrocyclones) generates another source of refuses accounting for more than a 55 % of the total plant refuse generation. Physico-chemical characterization of the samples from dry and wet anaerobic digestion plants shows that dry pre-treatment refuse and the light fraction from the pulpers are the refuse streams with the highest moisture and volatile solids content. Volatile solids were considered equal to biodegradable organic matter content in the following samples: (i) light fraction pulpers, (ii) HP & HC and (iii) compost refuses. On the contrary, during sampling, it was observed that dry-pretreatment refuse contained a significant amount of easily combustible plastics, therefore, the organic matter content of this refuse stream is better represented by the results obtained from manual characterization (Table 1). For both anaerobic digestion technologies assessed, the most prevalent material found in dry-pretreatment refuse corresponded to organic waste, followed by plastics and paper. The heavy fraction of pulpers and hydrocyclones is the refuse stream that shows the lowest value for MC and VS parameters, explained due to the fact that it is mainly composed by relatively inert material such as sands, bones and glass. The characterizations of dry pretreatment samples are in accordance with published data obtained at anaerobic digestion plants, for example Pognani et al. (2012) reported that more than 50 % of refuses corresponded to organic fraction (wet basis).

3.2. Cumulative biogas production

The cumulative amount of biogas produced ranged from 11.2 to 181.6 NL biogas/kg DM for 21-day test, and from 44.6 to 265.8 NL biogas/kg DM for the 100-day estimation (Table 2). The samples with the highest biogas potential corresponded, in decreasing order to: light fraction of pulpers, dry pre-treatment refuse, heavy fraction of pulpers and hydrocyclones; and finally, compost refuse. As indicated above, in the case of the dry pre-treatment refuse, organic matter content considered is the one given by manual characterization. As expected, the higher the organic matter content of the sample, the higher its biogas production potential with the exception of the compost refuse. In spite of its high VS content, this was the sample with the smallest biogas production potential, which is explained by virtue of the fact that this particular waste stream has already undergone both, anaerobic and aerobic degradation within the anaerobic digestion facility.

Experimental data obtained, together with plant production data provided by plant managers, permitted the calculation of a number of indicators outlined in Table 2. The first comparison is based on the efficiency of each plant to benefit from OFMSW to produce biogas. In this particular case, wet anaerobic digestion showed a better performance not only in terms of plant biogas production efficiency, but also digester production efficiency.

The second comparison is based on the refuse generation associated to each technology. First, it is possible to observe that wet anaerobic digestion generates larger amounts of refuse. The digester needs a feed with lower content of improper materials achieved through a more meticulous pre-treatment that generates larger quantities of refuse. In addition, it is also important to highlight that the refuse generated is biologically more active, represented by a higher biogas potential measurement. Consequently, from the point of view of biogas loss in the refuses, dry anaerobic digestion has a higher efficiency and a larger amount of the organic matter content of the OFMSW input is exploited inside the digesters.

Figure 2 shows biogas potential by each plant waste streams in Nm^3 of biogas per ton of OFMSW treated, compared to the actual biogas production. When considering a 21-day scenario, consistent with typical residence time in the digesters, biogas lost in refuses is between 8% and 15% of the plant production, the highest value corresponding to the wet anaerobic digestion technology. Instead, if the biogas production that takes place at the landfill site is considered (GB100 test), this values scale up to 16% to 24%. Pognani et al. (2010 and 2012) reported higher biogas production in both dry pre-treatment reject (343 NL biogas/kg DM) and compost reject (21 NL biogas/kg DM) which means that the biogas production lost in AD facilities could increase up to values close to 30 %. In view of these results, and non-negligible amount of biogas is lost and it becomes essential to evaluate how to mitigate biogas emissions (and benefit from them, whenever possible) and to reduce the landfill destination of organic material.

3.3. Life Cycle Analysis

Data on all input and output flows was obtained from plant managers as well as previously described experiments carried out on the samples. The main input and output materials and energy flows of each treatment plant are represented in Table 3. All data is related to 1 ton of treated OFMSW.

Table 4 specifies how each refuse stream contributes to the overall value of the environmental impact indicator, in particular, for dry-pre-treatment refuse the contribution of each material is detailed. Dry pre-treatment refuse is a major contributor for all six impact categories studied. This waste stream is particularly important in the dry anaerobic digestion facility, where it represents almost 70% of the total refuse (see Table 1). When taking into account the contribution of each type of material, biowaste is the major contributor, followed by plastics and paper, with the exception of the climate change category, where paper is the second major contributor due to its biogas production potential. In the case of wet anaerobic digestion, considerable contributions also come from the light fraction of the pulpers which represents almost 40% of the total refuse.

Figure 3 shows the contribution of each refuse stream to each one of the six impact categories studied. In the case of climate change, the GWP100 indicator is due to landfill biogas leaks to the environment and GHGs emissions due to landfilling operations. For the latter, the larger the amount of refuse being landfilled, the larger the impact. In the case of LFG leaks, the most important gaseous emissions are methane emissions and thus, it becomes important to analyze not only the amount of waste being landfilled but also its biological activity. The values of GB_{21} and GB_{100} measured indicate that wet AD facilities generate more active refuses. Particularly, waste streams generated during wet pre-treatment operations are the ones with the higher biogas potentials. Dry AD does not generate this type of refuses which translates into a considerably smaller carbon footprint.

For the remaining five environmental impact categories, the value of the corresponding mid-point indicator is proportional to the amount of waste sent to landfill. Therefore, the results obtained for dry anaerobic digestion are between 60% and 70% of the corresponding values obtained for wet anaerobic digestion. It is important to mention that in the case of photochemical oxidant formation, methane emissions occurring at the landfill site account for approximately 50 % of the overall POFP value and it becomes important to consider both, amount of waste landfilled and nature of the occurring emissions.

In view of these results, several possible improvements were suggested to ameliorate the environmental performance of the systems studied. It was observed that a considerable amount of organic material is lost in pre-treatment operations, so it is strongly encouraged to recover and send to digesters as much biowaste as possible, by either improving the efficiency of pre-treatment operations and/or, even better, by improving source selection. Other possible contributions would be to biostabilize refuses in composting tunnels prior to landfilling and to improve the landfill biogas collection efficiency. In order to determine the convenience of the proposed modifications, it would be necessary to perform system expansion and take into consideration both, the MBT facility itself and landfilling of the refuses generated.

4. Discussion

In order to perform a solid comparison among the different treatments applied to the organic fraction of municipal solid waste (OFMSW), it becomes essential to understand which type of refuse streams are generated and what are the potential impacts associated to them.

Rejected materials from pre-treatment and post-treatment of real full-scale anaerobic digestion plants have shown a considerably high organic matter content. These operations, that are intended to separate improper and inert material, have demonstrated a low efficiency, as a non-negligible amount of the organic matter of the OFMSW input is lost in the refuses. In particular, dry pre-treatment refuse and the light fractions of pulpers are the waste streams with the highest OM content observed. The first one had an organic fraction that accounted for 43 to 56% of the total dry weight of the sample, while the second one showed a volatile solids content of almost 85%.

Besides determining the type of materials present in the refuses, it is also relevant to evaluate their biological activity, and particularly, their biogas production potential. In accordance with the organic matter determination conducted on each sample, the highest biogas production potential corresponded to the floating fraction from pulpers (265 NL biogas/kg DM), dry pre-treatment refuse (157-200 NL biogas/kg DM) and the heavy fraction from pulpers and hydrocyclones (97 NL biogas/kg DM). The results obtained indicate that the biogas production potential of the refuses may be up to 60% of the mean value observed for OFMSW samples.

In view of these results, the anaerobic digestion plants studied are losing up to 15% of the plant's production capacity in their refuses. Particularly, major losses were observed for wet anaerobic digestion plant, not only because it generates more refuse but also because these refuse streams are biologically more active (wet pre-treatment refuses).

The anaerobic digestion plants studied were compared taking into account their main function, which is to treat the organic fraction of municipal solid waste. To make an even comparison, all flows were referred to the treatment of 1 ton of OFMSW. From data obtained in this study, based on the biogas production efficiency of each plant and the amount and type of refuse generated and taking into account the limits of the system, it has been found dry anaerobic digestion to be a more environmentally friendly technology for managing biowaste than wet anaerobic digestion.

This first conclusion was ratified by the results obtained from the Life Cycle Assessment conducted on each system. Dry anaerobic digestion showed a better environmental performance in the six environmental impact categories studied: climate change, ozone depletion, photochemical oxidant formation, terrestrial acidification, freshwater eutrophication and fossil depletion. Specifically, the value obtained for its environmental impact potentials were 40 to 70% of the corresponding values for the wet anaerobic digestion plants.

It is important to point out that only two plants were evaluated in this study, and to assure the convenience of one technology over another more facilities should be considered. These additional data would provide a solid base to determine which is the most sustainable and efficient way of treating the source-selected organic fraction of municipal solid waste.

5. Conclusions

The environmental performance of two anaerobic digestion plants have been evaluated in terms of its rejects streams. It has been found that biogas production in anaerobic digestion facilities is not optimized due to organic matter losses during the pretreatment stages, the biogas potential lost ranges from 8 to 15 % in dry and wet anaerobic digestion facilities respectively.

From an environmental point of view, dry anaerobic digestion facilities showed a better performance in all six categories of Life Cycle Assessment named climate change, ozone depletion, photochemical oxidant formation, terrestrial acidification, freshwater eutrophication and fossil depletion.

The results obtained in this work are novel and necessary to perform reliable Life Cycle Assessments of the overall management and treatment of biowaste in European countries, and have shown that although remarkable advances have been made in biowaste management, there is still a lot to be done as regards the refuses generated by them.

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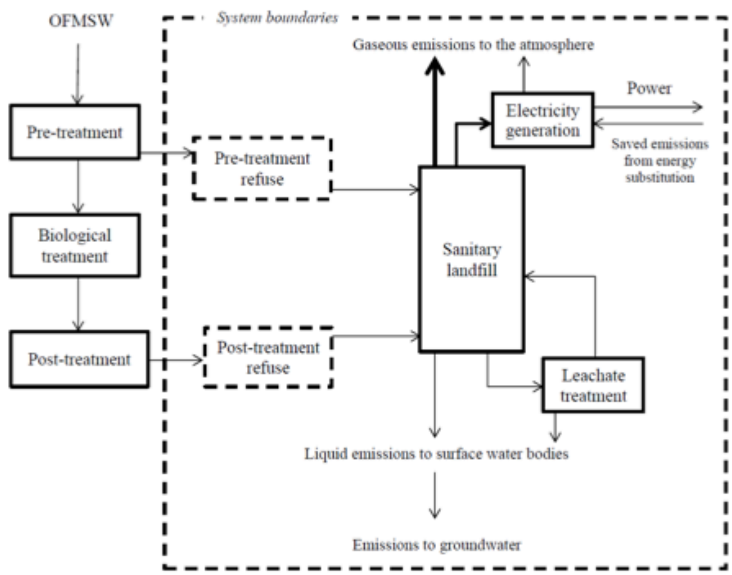
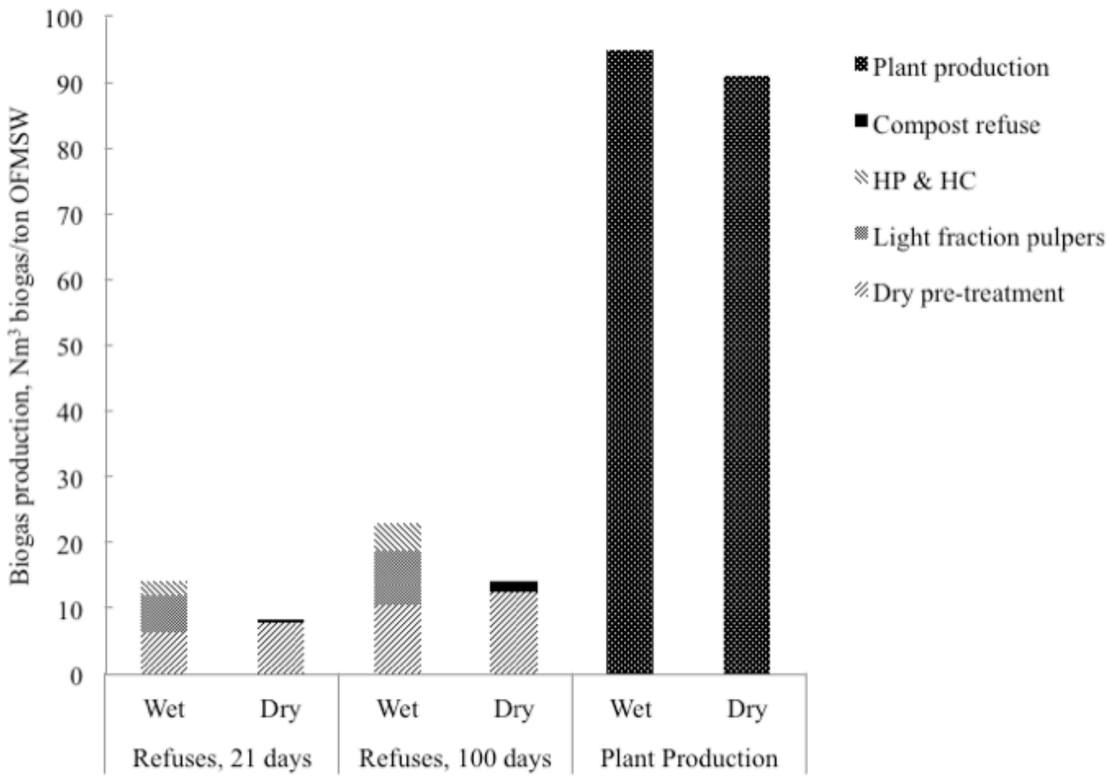
List of figures


OFMSW
System boundaries
Gaseous emissions to the atmosphere
Power
Electricity generation
Saved emissions from energy substitution
Pre-treatment
Pre-treatment refuse
Biological treatment
Sanitary landfill
Post-treatment
Post-treatment refuse
Leachate treatment
Liquid emissions to surface water bodies
Emissions to groundwater


100
90
80
70
60
50
40
30
20
10
0
Biogas production, Nm³ biogas/ton OFMSW
Plant production
Compost refuse
HP & HC
Light fraction pulpers
Dry pre-treatment
Wet
Dry
Wet
Dry
Wet
Dry
Refuses, 21 days
Refuses, 100 days
Plant Production

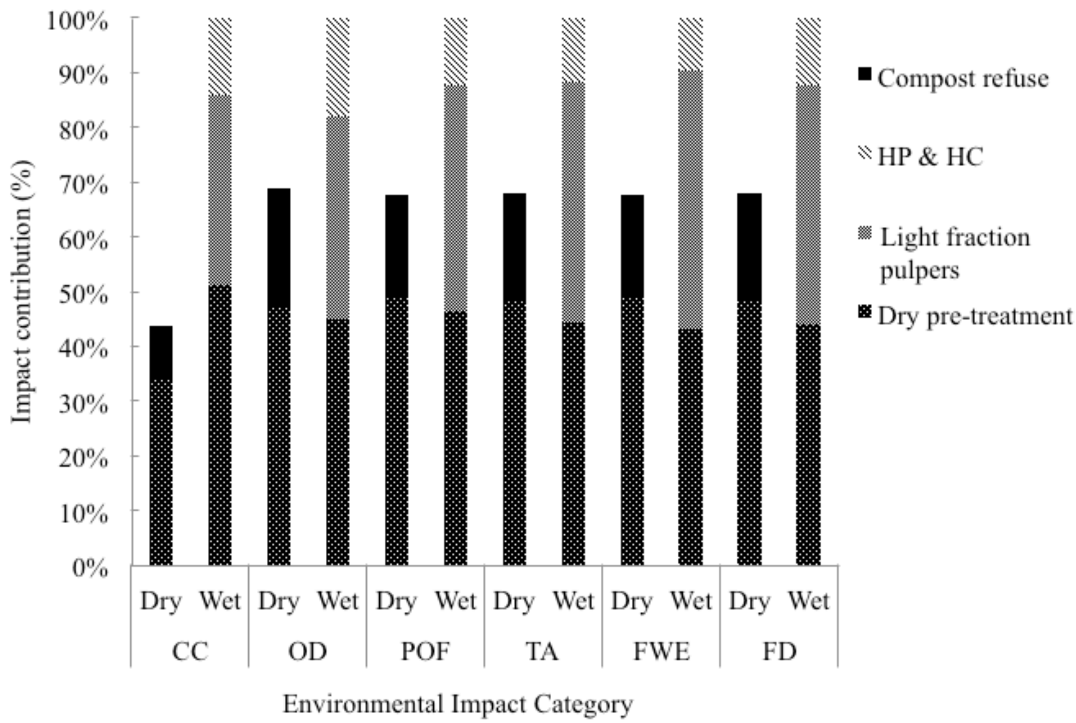

100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Impact contribution (%)
Compost refuse
HP & HC
Light fraction pulpers
Dry pre-treatment
Dry Wet Dry Wet Dry Wet Dry Wet Dry Wet Dry Wet
CC OD POF TA FWE FD
Environmental Impact Category

Table 1 Physico-chemical characterization of refuse streams.

Facility		Dry AD			Wet AD		
Refuse		Production (tons/ton OFMSW)	MC (% wb)	VS (% db)	Production (tons/ton OFMSW)	MC (% wb)	VS (% db)
	Dry pre-treatment	0.16	60.96 ± 1.09	80.09 ± 2.75	0.15	58.97 ± 1.24	88.68 ± 1.37
	Light fraction pulpers	n/a	n/a	n/a	0.13	75.49 ± 2.39	85.72 ± 7.78
	HP & HC	n/a	n/a	n/a	0.06	28.08 ± 3.31	17.73 ± 2.52
	Compost refuse	0.07	45.81 ± 0.75	38.27 ± 2.99	n/a	n/a	n/a
Dry pretreatment composition		Fraction (% in db)			Fraction (% in db)		
	Metal	n/d			1.33		
	Textile	0.96			1.63		
	Organic	22.61			17.11		
	Paper	1.69			3.78		
	Plastics	15.19			15.87		
	Glass	0.26			n/d		
	Water	59.30			60.28		

HP & HC: heavy fraction of pulpers and hydrocyclones.

db: dry basis

n/a: not applicable

n/d: not detected

Table 2 Biogas production potential of refuses and plant performance indicators.

Facility			Dry AD		Wet AD	
Properties		Unit	GB		GB	
			21	100	21	100
	Dry pre-treatment	NL biogas/kg DM	123.89 ± 46.90	199.28 ± 66.05	94.00 ± 12.86	157.19 ± 18.12
	Light fraction pulpers	NL biogas/kg DM	n/a	n/a	181.60 ± 45.63	265.84 ± 59.26
	HP & HC	NL biogas/kg DM	n/a	n/a	51.93 ± 9.60	97.44 ± 12.46
	Compost refuse	NL biogas/kg DM	11.20 ± 0.69	44.55 ± 0.90	n/a	n/a
Indicators						
	Plant production efficiency	Nm^3 biogas/ton OFMSW	90.95		95	
	Digester production efficiency	Nm^3 biogas/ton $OFMSW_{digester}$	118.53		143.29	
	Refuse generation	tons refuse/ton OFMSW	0.23		0.34	
	Overall refuse biological activity	Nm^3 biogas/ton refuse	36.62		49.19	
	Atmospheric emissions	Nm^3 biogas/ton OFMSW	8.52		16.58	

HP & HC: heavy fraction of pulpers and hydrocyclones.

n/a: not applicable

OFMSW: OFMSW that enters the production line.

OFMSW digester: OFMSW that actually enters the digester(s), after pre-treatment operations.

Table 3 Life cycle inventory. Data related to 1 ton of processed OFMSW.

			Unit	Dry	Wet
Inputs	Raw materials	OFMSW	ton	1	1
Outputs	Dry pre-treatment refuse	Metal	kg/ ton OFMSW	-	1.99
		Textile	kg/ ton OFMSW	2.94	2.44
		Organic[a]	kg/ ton OFMSW	190.27	111.16
		Paper	kg/ ton OFMSW	7.66	6.39
		Plastics	kg/ ton OFMSW	53.59	28.02
		Inert material	kg/ ton OFMSW	24.31	-
	Light fraction pulpers	Organic[b]	kg/ ton OFMSW	n/a	122.88
		Inert material	kg/ ton OFMSW	n/a	4.62
	HP & HC	Organic[c]	kg/ ton OFMSW	n/a	24.26
		Inert material	kg/ ton OFMSW	n/a	35.24
	Compost refuse	Organic[d]	kg/ ton OFMSW	48.4	n/a
		Inert material	kg/ ton OFMSW	24.31	n/a
	Atmospheric emissions	Methane	kg CH4/ton OFMSW	3.42	5.68
	Electricity		MJ/ton OFMSW	28.49	47.33

HP & HC: heavy fraction of pulpers and hydrocyclones.

n/a: not applicable

a: organic material from dry pre-treatment refuse of the corresponding plant.

b: organic material from light fraction of pulper of the corresponding plant.

c: organic material from the heavy fraction of pulpers and hydrocyclones from the corresponding plant.

d: organic material from the compost refuse of the corresponding plant.

Table 4 Impact characterization results: specific contributions from each refuse.

Impact category	Unit	Facility	Dry pre-treatment refuse						Light fraction pulpers	HP & HC	Compost refuse	Total
			Metal	Textile	Organic	Paper	Plastic	Glass				
CC	kg CO_2 eq	Dry	-	0.52	73.16	3.41	2.57	0.01	n/a	n/a	23.33	103.00
		Wet	0.04	0.83	109.74	7.18	2.51	-	81.95	32.76	n/a	235.01
OD	kg CFC-11 eq	Dry	-	4.56E-09	3.74E-07	1.04E-08	8.92E-08	1.27E-09	n/a	n/a	2.19E-07	6.98E-07
		Wet	8.48E-09	7.23E-09	3.29E-07	2.18E-08	8.71E-08	-	3.79E-07	1.81E-07	n/a	1.01E-06
POF	kg NMVOC	Dry	-	0.001	0.047	0.002	0.004	0	n/a	n/a	0.021	0.075
		Wet	0.000	0.001	0.042	0.004	0.004	-	0.05	0.01	n/a	0.112
TA	kg SO2 eq	Dry	-	0.001	0.039	0	0.002	0	n/a	n/a	0.017	0.059
		Wet	0.000	0.001	0.034	0.001	0.002	-	0.04	0.01	n/a	0.089
FE	kg P eq	Dry	-	0	0.058	0	0	0	n/a	n/a	0.022	0.080
		Wet	7.03E-06	3.66E-04	5.10E-02	3.09E-05	3.75E-05	-	0.06	0.01	n/a	0.121
FD	kg oil eq	Dry	-	0.04	3.05	0.02	0.20	0.00	n/a	n/a	1.34	4.65
		Wet	0.02	0.06	2.68	0.05	0.20	-	3.00	0.83	n/a	6.84

HP & HC: heavy fraction of pulpers and hydrocyclones.