# ENVIRONMENTAL BURDENS OF MUNICIPAL BIOWASTE MANAGEMENT: THE CASE OF CATALONIA

Joan Colón[1], Erasmo Cadena[1], Ana Belen Colazo[1], Roberto Quirós[2], Antoni Sánchez[1], Xavier Font[1] and Adriana Artola[1]

*[1] Composting Research Group. Department of Chemical Engineering. Universitat Autònoma de Barcelona. Bellaterra, Barcelona (Spain)*

*[2] SosteniPrA Research Group, Institute of Environmental Science and Technology (ICTA), Universitat Autònoma de Barcelona, 08193 Edifici C Bellaterra (Barcelona), Spain*

Contact: Joan Colón, Universitat Autònoma de Barcelona, Departament d'Enginyeria Química, Escola d'Enginyeria, Edifici Q, Campus de Bellaterra, 08193- Cerdanyola del Vallès, Spain. Tel.: +34935814793, Fax.: +34935812013, e-mail address: joan.colon@uab.cat

**Abstract**

The Organic Fraction of Municipal Solid Waste (OFMSW), or biowaste, can be valorized using different treatment technologies, such as anaerobic digestion and composting or the combination of them. The use of the end products (biogas and/or compost) generates benefits over the alternative of sending waste to landfill. The European Union regulations (i.e. Landfill Directive) encourage the diversion of untreated biodegradable waste from landfilling. However, OFMSW treatment installations also produce environmental impacts that must be assessed. This paper presents different future scenarios at regional scale proposed to accomplish the Landfill Directive and their environmental assessment in terms of environmental impact potentials. The geographical area under study is Catalonia (Spain).

Field data obtained in previous studies undertaken in the same geographical area are used to determine the environmental burdens of the present situation in order to compare them with different future scenarios. The current Catalan waste management scenario (ISc1) treating 1,218 Gg of organic wastes is analyzed by means of a LCA tool. A new scenario

(LFD1) fulfilling the European landfill directive and the new recently approved Catalan waste management plan (PRECAT 2014-2020) is compared with the initial scenario. The main requirements of this new legislation are: (i) at least 60 % of organic municipal solid wastes must be source selected and valorized and (ii) 100 % of non-source selected municipal solid waste (MSW) must be treated at mechanical biological treatment plants (MBT) before its final disposal. The new LFD1 scenario decreases the environmental impact in 5 out of 6 analyzed impact categories (global warming, abiotic depletion, acidification, eutrophication, ozone layer depletion) and only one impact category (photochemical oxidation) shows a higher impact.

**Keywords**

*Environmental impact, OFMSW treatment, Composting, Anaerobic digestion, Impact potentials, Waste treatment scenarios.*

**Abbreviations**

LCA: Life Cycle Assessment

LFD: Landfill Directive (European Union)

OFMSW: Organic Fraction of Municipal Solid Waste

VOC: Volatile Organic Compounds

*Waste Treatments:*

AD: Anaerobic Digestion

AWB: Aerated Windrows Composting with gaseous emissions Biofiltration

AWC: Aerated Windrows Composting

CT: In-vessel Composting

HC: Home Composting

TWC: Turned Windrows Composting

*Impact potentials:*

ADP: Abiotic Depletion Potential

AP: Acidification Potential

EUP: Eutrophication Potential

GWP: Global Warming Potential

OLDP: Ozone Layer Depletion Potential

POP: Photochemical Oxidation Potential

## 1. Introduction

Our daily activities inevitably lead to waste generation. Specifically, in the European Union, each person generated an average amount of 1.40 kg of waste per day in 2010 (Eurostat 2013). The Landfill Directive published in 1999 by the European Union (Council of the European Union 1999) requires its Member States to reduce the quantity of biodegradable waste ending up untreated in landfill sites by adopting measures to increase and improve waste reduction, recovery and recycling. For the organic fraction of municipal solid waste (OFMSW) or biowaste, separation at the source and treatment through anaerobic digestion and/or composting appear to be the most sustainable options. The Green Paper on the Management of Bio-waste in the European Union (European Commission 1999) considers that the environmental impact of composting is mainly limited to some greenhouse gas emissions and volatile organic compounds. It also states that in composting the impact on climate change due to carbon sequestration is limited and mostly temporary, and that an adequate control of input material and the monitoring of compost quality are of great importance. Relating anaerobic digestion, the Green Paper highlights that, as this treatment is conducted in closed reactors, the emissions to the air are significantly lower and easier to control than from composting. In addition to this, every Mg of biowaste sent to biological treatment can deliver 100-200 $m^3$ of biogas. The energy recovery potential from biogas coupled with the soil improvement potential of residues (especially when treating separately collected biowaste) make anaerobic digestion the environmentally and economically most beneficial treatment technology. Also, home composting is considered in that document confirming that this is sometimes regarded as the environmentally most beneficial way of handling domestic biodegradable waste due to savings on transport emissions and costs. Home composting also ensures careful input material control and increases the environmental awareness of the users.

The use of compost improves soil structure, provides organic matter and increases its water holding capacity. On the other hand, the use of compost partially avoids the use of chemical fertilizers (which production generates important environmental impacts) (Martinez-Blanco et al. 2009). In the case of biogas, its use in electricity production avoids the consumption (and production) of electricity from potentially more polluting and non-renewable sources. Furthermore, the use of waste heat in electricity production from biogas to maintain the temperature of anaerobic digesters can reduce even more the consumption of external energy in waste treatment facilities.

However, as any industrial process, the treatment of the OFMSW inherently generates environmental impacts that must be assessed. During the process there is energy consumption, emissions are released to the atmosphere and leachate is generated, among other impacts. These impacts can be different depending on the technologies used for the treatment of waste. However, due to the wide number of technologies and waste collection systems it is necessary to collect real local data on each management system to generate reliable information on the environmental inventories. This information can be used to complete a Life Cycle Inventory or, in waste management systems modeling, to compare facilities, to make decisions on a specific technology or in regional greenhouse gases inventories.

Many of the studies related with the environmental impact of municipal solid waste treatments have been performed at laboratory scale (Smet et al. 1999; Komilis et al. 2004; Pagans et al. 2006). However, literature can also be found on the global impact of a specific technology or facility by using in situ measurements (Komilis & Ham 2000; Bernstad et al. 2001; Boldrin et al. 2011). This is the case, for example, of Blengini (2008), who used the Life Cycle Assessment (LCA) methodology to evaluate the environmental impacts of a composting plant in Italy. The results indicate that emissions generated during the composting process are mainly the large group of volatile organic compounds (VOC), methane ($CH_4$), nitrous oxide ($N_2O$) and ammonia ($NH_3$). All these compounds can generate environmental impacts: VOC can cause odors, as ammonia, but may also participate in photo-reactions in the atmosphere resulting in oxidizing compounds such as ozone. Methane and nitrous oxide have a high global warming potential. It is also important to determine which VOC are emitted. In this area few studies can be found; among them, Orzi et al. (2010) determined the VOC emitted during the anaerobic digestion of the OFMSW at a full scale treatment facility.

Biological treatment processes also produce, directly and indirectly, $CO_2$ emissions. However, $CO_2$ emissions from biological processes are generally not taken into account in greenhouse gases inventories as they come from a biogenic source (Guinée 2002; IPPC 2006), but evidently, $CO_2$ emissions from energy consumption (electricity or diesel) must be determined and considered. Then, the use of biogas for cogeneration (heat and electricity production) should be a key factor in the reduction of $CO_2$ emissions in the waste management sector.

Regarding management systems modeling, some literature can be found on municipal solid wastes, for example: EASEWASTE (Kirkeby et al. 2006), ORWARE (Sonesson et al. 1997) and WASTED (Diaz & Warith 2006), which are simulation tools that include the environmental burdens associated to waste management. LCA has also been applied to generic waste management systems (De Feo & Malvano 2009) and to MSW management systems of different cities or regions such as Wales (Emery et al. 2007), Ankara (Özeler et al. 2006), Phuket (Liamsanguan & Gheewala 2008), Corfu (Skordilis 2004) or Delaware (Kaplan et al. 2009). Other authors have focused their research on the environmental impact of the different waste collection options (Iriarte 2009). Some of these works include a great effort to obtain real local data to perform the study, a point that is crucial to obtain reliable conclusions.

This work has two main goals: (i) To estimate the current environmental impacts caused by the management of the OFMSW in Catalonia and (ii) to estimate the future environmental impacts caused by the management of the OFMSW in Catalonia, the future management scenario is designed to fulfill the European Union Landfill Directive in terms of biodegradable waste diversion. To accomplish this objective, inventory data obtained in previous studies from five different full-scale treatment plants in the same geographical area has been used. Also real data from home composting experiments has been used.

## 2. Methodology

### *2.1. Area studied*

The area under study corresponds to Catalonia, in the Mediterranean coast of Europe (North-East of Spain). Catalonia has an extension of approximately 32000 $km^2$ and a population of 7,539,000 inhabitants (2011). In 2012 the municipal waste generation was of 3,731 Gg from which 1,457 Gg (39 %) was source-selected. Previous and existing waste management plans in Catalonia clearly supports the source-selection of all the fractions of municipal solid wastes. Waste fractions considered in source-collection are: organic waste (OFMSW or biowaste), paper and cardboard, glass, plastics and light packaging and refuse. Regarding the OFMSW, 384 Gg were collected in 2012 (all of them source-selected) plus 99 Gg of pruning waste (Catalan Waste Agency 2014). Pruning waste is used as bulking agent during composting in some treatment plants. A complete waste classification and sorting scheme can be found in the reports published by local administrations such as the Catalan Waste Agency (2014).

Table 1 shows the current composition of MSW generated in Catalonia and Table 2 shows the amount of source-selected and non source-selected OFMSW and its treatment/disposal destination.

## *2.2. Life cycle assessment*

### *2.2.1. General Methodology*

LCA is a methodology for the determination of environmental impacts associated to a product, process or service from cradle to grave, in other words, from production of the raw materials to ultimate disposal of waste. According to ISO 14040–14044 (International Organisation for Standardisation 2006), there are four main steps in a LCA study: the goal and scope definition, the inventory analysis, the impact assessment and the interpretation. In this study, the software SimaPro v. 7.1.8 (PRé Consultants 2008) was used to evaluate the environmental impacts of all waste treatment technologies considered. Only the obligatory phases defined by the ISO 14040–14044 regulation for the impact assessment (International Organisation for Standardisation 2006), namely classification and characterization, were performed as they avoid the subjectivity involved in impact evaluation (Martínez-Blanco et al. 2009). The impact assessment method used was CML 2001, which was based on the CML Leiden 2000 method developed by the Centre of Environmental Science of Leiden University (Guinée 2002). The impact categories considered were: abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion potential (OLDP) and photochemical oxidation potential (POP).

### *2.2.2. Goal of the study*

There were two main objectives in this environmental study: Firstly, to evaluate the current environmental impacts generated during the OFMSW treatment in Catalonia and to detect the contribution of each treatment technology to the overall impact. Secondly, to propose a coherent future scenario fulfilling the requirements of EU Landfill Directive and the new recently approved Catalan waste treatment program (PRECAT 2014-2020) in terms of organic waste diversion from landfill and minimizing the environmental impacts related to OFMSW treatment. The results of this study should be considered as a decision making tool, and although this study is focused on Catalonia, the results could also be used when planning new regional treatment policies.

### *2.2.3. Functional unit*

The key functions for all the technologies considered were the management of the OFMSW. The functional unit (FU) in LCA provides a reference to which the inputs and outputs of the inventory are related and allows the comparison among systems (International Organisation for Standardisation 2006). In this study the functional unit (FU) selected was the management by composting or anaerobic digestion of one Mg of OFMSW.

### *2.2.4. Description of the system*

Figure 1 shows the stages of the two systems considered in this LCA. Figure 1.a shows the current organic waste management model, and Figure 1.b shows a proposed management model with the necessary modifications to fulfill the EU Landfill directive.

The impacts derived from plant and machinery construction were not included because of, in a previous study (Martinez et. al. 2010), the overall contributions in all impact categories was less than 2.5 %.

### *2.2.5. Main hypothesis*

#### *2.2.5.1. Biodegradable orgànic waste treatment*

The amount of source-selected OFMSW (SS-OFMSW) treated at each installation has been directly taken from data provided by the Catalan waste agency (ARC, 2014). In the SS-OFMSW input stream, 15 % of impurities were measured (ARC, 2014). Regarding home composting, 0 % of impurities were considered.

In order to estimate the amount of non source-selected OFMSW (NSS-OFMSW) that ends up to incineration or sanitary landfill, the total amount of mixed municipal solid waste was multiplied by its average organic fraction content (39 %). Organic refuses coming from source-selected and non source-selected treatment plants also ends up to a final disposal destination, a previous study (data not published) estimated that an average amount of 100 kg OFMSW/t SS-OFMSW and 250 Kg OFMSW/t NSS-OFMSW were lost during the pretreatment process, these amounts of refuses are also considered in the LCA.

#### *2.2.5.2. Transport*

In this study, both urban transport collection (Iriarte et al, 2009) and transport intercity to the plant were considered (Iriarte et al., 2009). A 21 ton MAL lorry specifically designed for waste collection was considered (Ecoinvent 2). The average distance from the collection points to the treatment facilities (composting and MBT facilities) in Barcelona metropolitan area is close to 10 km (Martinez-Blanco et al., 2010), impacts of return trips made by the trucks were also attributed. This average distance has been used for all the source-selected OFMSW collected in Catalonia. No transport was considered for home composting. Although there is not reliable data on average distances from collection areas and its final disposal facilities (incineration and sanitary landfill), taking into account the main populations and the distance to its final disposal installations an average distant from collection areas of 5 km and 20 km are assumed for incineration facilities and sanitary landfills respectively.

*2.2.5.3. Greenhouse gas emissions*

Regarding $CO_2$ emissions from the biological treatment process, these have not been considered in impacts calculation due to the general consensus (IPPC) that $CO_2$ from these type of treatments is of biogenic origin and does not add to the overall emissions that contribute to global impacts (IPPC 2006).

Biogas emissions in anaerobic digestion plants were measured only on biofilter surfaces, the fugitive emissions from other sources (pipes, pressure release from the reactor, flared biogas) have been considered close to zero following IPPC recommendations as no experimental measurements were possible (IPPC 2006). However, some studies (Moller 2009) showed fugitive emissions ranging from 0 to 10 % of the total methane produced, for this reason sensitivity analysis including a 5 and a 10 % fugitive emissions plus the combustion of biogas has also been included. Since 98.8 $m^3$ biogas $Mg^{-1}$ OFMSW were produced during the studied anaerobic digestion process and assuming average methane content of 65 %, a total fugitive emissions of 2.3/4.6 kg $CH_4$ $Mg^{-1}$ OFMSW were considered. During combustion in biogas engines, methane is converted to energy and $CO_2$, but as the combustion process is not 100% efficient some methane is left unburned and in this way contributes to the GWP, a total amount of 0.8 kg $CH_4$ $Mg^{-1}$ OFMSW (Moller 2009) was considered. Thus a total amount of 3.1/5.4 kg $CH_4$ $Mg^{-1}$ OFMSW can be considered when fugitive emissions are taken into account. The fugitive emissions accounted for 57.5/115 kg $CO_2$ eq. $Mg^{-1}$ OFMSW and the combustion of biogas accounted for 20 kg $CO_2$ eq. $Mg^{-1}$ OFMSW.

### *2.2.6. Life cycle inventory: Quality and origin of the data*

Real data on source-selected OFMSW treatment facilities was obtained in previous works (Colon et al. 2012, Martinea-Blanco et al., 2010). In these works, a representative treatment facility of each type (AD, CT, AWC, TWC) was studied in detail to determine the environmental burdens associated to plant operation. The plants studied (5 treatment plants) were selected after a deep discussion with the Catalan Waste Agency (*Agència de Residus de Catalunya,* ARC) for real representativeness, as a detailed study of all plants in operation was out of the possibilities of the work. Inventory data on energy and water consumption, waste treated, impurities separation and compost produced (as well as biogas in the case of the anaerobic digestion installation) was obtained from plant managers. In addition, an accurate gaseous emissions sampling was undertaken in order to quantify the emissions of ammonia, volatile organic compounds (VOC), methane and nitrous oxide (the methodology can be consulted in Colón et al. 2012 and Cadena et al. 2009). Home composting was also studied as a treatment alternative for OFMSW in low-density population areas (Colon et al. 2010; Martínez Blanco et al. 2010). Table 3 summarizes the inventory data obtained in the above-mentioned previous studies (Colón et al. 2012, Martinez et al., 2010). This data has been used as the basis to perform the calculations presented in this paper. Aerated and turned windrows composting plants are not provided with gaseous emissions treatment equipment. Taking into consideration the impacts that can be derived from these emissions, a new type of treatment plant (AWB) has been added to Table 3. AWB represents a theoretical configuration (not experimentally studied) were composting occurs in aerated and turned windrows placed on a closed installation with gaseous emissions treatment using biofilters. Values on real biofilter efficiencies in contaminant removal were considered to determine reduced impacts (Amlinger et al. 2008; Colón et al. 2009) and are reflected in Table 3. Energy consumption associated to biofilter operation was considered as additional impact (also reported in Table 3) and obtained from Cadena (2009).

Regarding the treated NSS-OFMSW, most mechanical biological treatment plants (MBT) rely on composting tunnels plus a curing phase and to a lesser extent anaerobic digestion plus curing phase. The environmental burdens of these operations are related to energy consumption (tunnel and building ventilation, fuel consumption, etc.) and gases emissions/treatment. All these phases are considered in the LCA of source-selected composting tunnel (CT) and anaerobic digestion plants (AD) including also the energy recovery. The main difference is the extra energy needed at the pretreatment stage, but the allocation of this extra energy consumption should be accounted to the material recovery stage (packaging, metal, paper and cardboard). Therefore, in this work the environmental impact of MSW-MBT (MSW-AD & MSW-CT) plants is considered the same as the environmental impact related to SS-OFMSW treatment (CT or AD facilities).

Table 4 summarizes the values calculated for the different impact potentials for each of the studied plants related to the treatment of 1 Mg of OFMSW.

Finally, in order to calculate the impact potentials of NSS-OFMSW and OFMSW refuses disposed at incineration facilities or sanitary landfills, data coming from ELCD database specifically compiled for the Mediterranean region were used. The modeled landfill includes energy recovery (Distribution of landfill gas: 22 % flare, 28 % used, 50 % emissions) and leachate treatment. The modeled incineration also includes energy recovery and ash disposal to sanitary landfill.

### *2.3. OFMSW treatment scenarios definition*

To accomplish the goals of this study two main scenarios have been considered to calculate the environmental burdens of OFMSW treatment in Catalonia: Scenario 1 (ISc1) (Figure 1.a) corresponds to the current situation and the results obtained from it will show the current environmental impact generated during the OFMSW management and the contribution of each specific treatment technology in the overall impact. Scenario LFD1 (Figure 1.b) represents a hypothetical future situation fulfilling the requirements of EU Landfill Directive in terms of organic waste diversion from landfill.

*Scenario 1*

This Scenario reflects the situation in 2012 where 22 installations were in operation treating source-selected OFMSW.

Some assumptions have been made to calculate the values of the impact potentials. First, it has been supposed that all the plants using the same treatment technology will produce the same impacts per Mg of OFMSW treated. Obviously, even with the same technology and presenting a very similar layout each plant has some particularities. However, the detailed study of all the individual plants in terms of environmental burdens calculation is beyond the scope of this study. The installations used were chosen as they were representative of each technology, including in the representativeness the fact that they are treating the same type of waste produced in the same region. It has been stated that the geographical variability of the waste characteristics is an important source of errors when inventory data is used from global databases (Fricke et al. 2005).

*Scenario LFD*

This hypothetical scenario treats the same amount of organic wastes as in in ISc1. This scenario would permit to fulfill the requirements of European Union Landfill Directive (Council of European Union 1999) and the recently approved Catalonia waste management plan (PRECAT 2014-2020). This scenario is based on two main premises: (i) 60 % of municipal organic wastes must be source-selected and valorized and (ii) 100 % of mixed MSW must be treated at MSW-MBT facilities. Therefore, the final disposal (incineration and sanitary landfill) of untreated MSW is not allowed.

Two main areas can be differentiated in Catalonia, the first one named metropolitan area of Barcelona which include Barcelona city and its nearby cities, this area is characterized by a high population density and a high degree of industrialization. The second one is the remaining part of Catalonia that is characterized by low-density population and in terms of waste management, still relies strongly on landfilling.

The metropolitan area of Barcelona has a total installed treatment capacity of 346.5 Gg and 1,310 Gg of SS-OFMSW and MSW respectively. The current installed capacity it is enough to treat all municipal wastes generated in this area and the construction of new installations is not expected. Moreover there is an extra AD treatment capacity originally designed to treat NSS-OFMSW that are currently out of use and could potentially be used as a SS-OFMSW treatment, as a result, there is total installed AD treatment capacity close to 404 Gg. Assuming a 60 % source selection of OFMSW, a total amount of 400 Gg will be generated and potentially could be treated by means of AD. The remaining NSS-OFMSW wastes generated in the metropolitan area of Barcelona will be treated at the currently in operation MSW-CT plants.

On the contrary, the remaining part of Catalonia lacks of both SS-OFMSW treatment plants and mainly MSW treatment plants. The total installed SS-OFMSW treatment capacity is close to 137 Gg, and an extra treatment capacity of 136 Gg will be necessary to accomplish the proposed regulation. Regarding MSW treatment plants only a treatment capacity of 444 Gg is currently installed, and it will be necessary the construction of new facilities to be able to treat the remaining MSW.

Assuming the abovementioned conditions the following assumptions will be made in the LFD1 scenario:

(i) All the SS-OFMSW generated in the metropolitan area of Barcelona will be treated by means of AD.

(ii) Some CT facilities are currently planned and/or being build, this new facilities are included

(iii) Because of AD it is the more environmental friendly technology, the new installations (not yet planned) will be designed using these technology.

(iv) Home composting treatment capacity will be increased up to 25 Gg.

(v) The AWC and TWC plants will be remodeled with a gas treatment installation (biofilters) to minimize the $NH_3$ and VOCs emissions (AWB facilities).

(vi) All NSS-OFMSW will be treated at MSW-CT plants

## 3. Results and discussion

### *3.1. Scenario 1*

For each treatment technology, Table 5 presents the number of installations in operation, the total Gg treated and the impact potential values calculated on a yearly basis using data from Table 4 and data from Ecoinvent (transport) and ELCD (sanitary landfill and incineration) dabatases.

As can be seen in Table 5, the OFMSW landfilled without any treatment (28 %) is the main responsible for the GWP (47.4 %) and EUP (55.2 %), these impacts are mainly related to air emissions (methane and ammonia) and water emissions (phosphates, ammonium). If the environmental impacts of landfilled refuses are also included the total GWP and EUP increases up to 60.8 and 85.6 respectively. The NSS-OFMSW treated at MBT facilities (36 %) has an environmental impact ranging from 2.5 to 35 % in all categories, its main contribution are in AP (26.5 %) and POP (35.6 %). On the contrary, Incineration (8%) has little impact (<5 %) in all categories.

The SS-OFMSW (27 %) is the main responsible for the AP (35.5 %) and POP (49 %); a closer analysis focusing on the type of source-selected treatment installations shows that treatment plants without gaseous emissions treatment (AWC and TWC) are the main responsible for AP (76.5 %), POP (52.5 %) and EUP (77 %) although they are only treating 14 % of the total amount of SS-OFMSW. These data demonstrate the contribution of the gaseous treatment equipment to the reduction of the impact of the OFMSW treatment plants in some of the impact potentials. However, the energy required by this equipment derives in higher contributions to GWP, ADP and ODP, as occurs in the case of CT plants. Biogas recovery in AD plants and the existence of gaseous emissions treatment result in relatively lower impact potential values

Finally transportation has its main impacts in ADP (40.3 %) and OLDP (66.5 %) and AP (20 %). Because of the amount treated and the longer distance to sanitary landfills from the collection point, the transportation of the NSS-OFMSW landfilled without any treatment is the responsible of 40 % of the total transport impacts.

### 3.1.1 ISc sensitivity analysis

As the results obtained correspond to a quite particular situation, environmental impacts for several hypothetical scenarios obtained by modifying relevant assumptions of the OFMSW management model were assessed and compared with initial scenario studied (ISc1) to perform the sensitivity analysis of the results. Four new assumptions were assessed: (i) the distance between the treatment/disposal installations and the collection point, (ii) the methane fugitive emissions in AD and MSW-AD plants, (iii) the efficiency of biogas collection in sanitary landfills and (iv) the use of compost as an organic amendment. Results are shown in Table 6.

A first scenario (ISc2) without considering the transport is proposed in order to highlight only the different treatment technologies. Figure 2.b shows the environmental impact of each treatment technology. Regarding ADP and OLDP, the two impact categories in which transport is the main responsible, landfilling and NSS-OFMSW treatment plants are the mains responsible with an overall contribution ranging from 20 to 45 %.

A distance of 5 km and 10 km between the collection point and the SS-OFMSW treatment facility and the sanitary landfill has been respectively considered (ISc3). Such situation may change as a function of the local distribution and restrictions of this kind of facilities. Impacts in scenario ISc3 considered half reduced distance and were significantly lower for ADP (14 %) and OLDP (23 %) impact categories, no significant reductions (<7 %) were measured for the remaining categories.

An important factor usually omitted is the methane fugitive emissions produced in AD and MSW-AD installations. Möller (2009) reported maximum methane fugitive emissions close to 10 %. Scenarios ISc4 and ISc5 have included in the inventory, fugitive emissions of 5 and 10 % respectively. Methane contributes mainly in GWP and in a lesser extent in POP. As can be seen, taking into account the whole management system an increase of 4 and 9 % of GWP is reported when fugitive emissions are considered. In terms of POP the increase is trifling (<2 %). Focusing on AD or MSW-AD installations itself, these fugitive emissions has a huge impact on GWP increasing up to 400 % (10 % fugitive emissions) its initial value considered in ISc1. These data must be taken into account when planning the LFD scenario, AD is the most suitable treatment technology, but fugitive emissions close to 10 % will eventually lead to a huge increase of GWP if AD is widely spread along Catalonia.

Landfill gas collection systems are assessed in ISc6. Although in ISc1 the biogas recovered is 50 % (22 % flared + 28 % energy recovery), several studies pointed out that the current biogas recovery in Catalonia could be as low as 17 % (Sostenipra, 2013); therefore a new scenario is modeled taking into account this amount of biogas recovery. In this situation, each ton of landfilled organic material releases to the atmosphere 786 kg $CO_2$ eq, and a significant increase of GWP (36 %) is observed.

Finally, the use of compost and also the use of biostabilized material as organic amendment are assessed in ISc7 and ISc8. Only its contribution in GWP is assessed, an avoided impact of 88 kg $CO_2$ eq/t compost (Sostenipra, 2013) which implies only a GWP reduction ranging from 2 to 5 %. The current legislation does not permit the use of biostabilized material as organic amendment, in consequence, the vast majority of biostabilized material is used a daily recovery of sanitary landfills.

### *3.2. Scenario LFD*

For each treatment technology, Table 7 presents the total Gg treated at each installation and the impact potential values calculated on a yearly basis using data from Table 4 and data from Ecoinvent (transport) and ELCD (sanitary landfill and incineration) databases.

Although fresh NSS-OFMSW is not landfilled without treatment, the refuses coming from both SS-OFMSW and NSS-OFMSW treatment facilities that ends up to sanitary landfill still have a significant impact in categories such as GWP, ADP and mainly EUP.

Landfill methane emissions still represent a total impact close to 28 % of the overall GWP and if the transport is not taken into account (Fig 3.b) this percentage increases up to 37 %. The same situation occurs regarding EUP, although the landfilled OFMSW is strongly minimized, it still is the main contributor to EUP with a total contribution close to 75 %. This data highlights the importance of improving both source selection and pretreatment processes in order to minimize the lost of fresh organic matter during pretreatment processes.

#### 3.2.1 LFD sensitivity analysis

Environmental impacts for several hypothetical scenarios obtained by modifying relevant assumptions of the OFMSW management model were assessed and compared with the initial scenario studied (LFD1) to perform the sensitivity analysis of the results. Five new assumptions were assessed: (i) transport is not considered, (ii) the use of CT instead of AD technologies, (iii) the methane fugitive emissions in AD plants, (iv) the efficiency of biogas collection in sanitary landfills and (v) the use of compost as an organic amendment. Results are shown in Table 8.

A first scenario (LFD2) without considering the transport is proposed in order to highlight only the different treatment technologies. Figure 2.b shows the environmental impact of each treatment technology. Regarding ADP and OLDP, the two impact categories in which transport is the main responsible, NSS-OFMSW treatment plants (MSW-CT) are the responsible of more than 60 % of the overall impact.

Due to higher capital costs and higher operation complexity, it is probable that AD will not be the main treatment technology applied to new facilities. Therefore two new scenarios are proposed (LFD3 and LFD4). LFD3 scenario uses all the current AD installed capacity (current facilities in operation and out of use reactors designed for treating NSS-OFMSW) but it is considered that all new installations will be using CT technologies, scenario LFD3 shows that the change in all impact categories is less than 5 %. On the other hand LFD4 keeps the same amount of Gg currently treated by AD and all the new SS-OFMSW will be treated by means of CT facilities (out of use AD reactors will not be used), in that case all the impact categories related to energy recovery/consumption (GWP, ADP, AP and OLDP) presents an increase ranging from 8 to 28 %.

AD treatment capacity in LFD1 scenario is more than two times higher than in ISc1, so it is of utmost importance the fugitive emissions control. LFD5 and LFD6 have included in the inventory, fugitive emissions of 5 and 10 % respectively. In the worst-case scenario the GWP could increase up to 31 %.

Landfill gas collection systems are assessed in LFD7 and LFD8. LFD7 as in the case of ISc6 uses only a 17 % of landfill gas recovery. On the contrary, the collection efficiency is increased up to 60 % in LFD8, this percentage of biogas recovery is the proposed as a goal by the Waste Catalan Agency (PRECAT, 2014). Due to only organic refuses are landfilled and the biogas recovery in LFD1 is 50 % (flared + used), a small difference is shown in LFD8. On the contrary an increase of 17 % is shown when biogas collection is decreases until 17 %.

Finally, the use of compost and also the use of biostabilized material as organic amendment are assessed in LDF9 and LFD10. Only its contribution in GWP is assessed. Due to the increase in source selection and also the amount of MSW treated at MBT plants, the production of compost and biostabilized material rises from 83 to 183 and from 110 to 121 Gg respectively. Reductions from 7 to 12 % are expected when these materials are used as an organic amendment.

### *3.3. Comparison of both scenarios*

Figure 4 shows the comparison of both waste management scenarios. The new LFD1 scenario decreases the environmental impact in 5 out of 6 impact categories; only POP shows a higher impact (23 %), this increase is mainly due to the higher VOCs emissions during composting processes compared with VOCs landfill emissions.

GWP shows a decrease of 36 % mainly because of the absence of landfilled NSS-OFMSW. It is important to remark that probably the current landfill biogas capture efficiency is close to 17 % and the goal is to achieve an efficiency of 60 %, therefore a comparison of scenarios ISc6 and LFD8 should be performed, in this situation a GWP decrease close to 55 % is achieved. If the use of compost coming from SS-OFMSW as an organic amendment is also taken into account a maximum decrease close to 58 % could be expected.

Abiotic depletion shows a decrease of 16 %, this impact reduction can be attributed to two different factors. The first one is related to the increase of the amount of organic wastes treated by AD facilities, Table 4 shows that because of the energy recovery in AD plants, there is an avoided impact in terms of ADP. The second factor is related to the decrease of intercity transport, treatment facilities are located at an average distance of 10 km while sanitary landfills are at an average distance of 20 km.

A decrease of 17 % is achieved regarding AP. In that case, the main contributors to this impact category are the treatment plants, especially the ones without gas treatment, ammonia and electricity consumption are the main contributors to this category. Consequently, the new AWB configuration proposed in this works as well as the increase of the amount of organic wastes treated by AD facilities (energy recovery) are the responsible of this decrease.

EUP has the highest impact reduction (49%). Again, this reduction can be attributed to two factors. Ammonia, ammonium and phosphates released from landfills are the main responsible of this impact; therefore the absence of landfilled NSS-OFMSW avoids a substantial part of this impact. Moreover, ammonia emissions from treatment plants, specially the ones without gas treatment, were also responsible for EUP, the new AWB proposed plants reduces up to 70 % the EUP compared with the TWC and AWC composting plants.

Finally, the OLDP potential is only reduced a 9 %, this decrease can be almost entirely attributed to the decrease of the transportation of NSS-OFMSW to landfills.

## 4. Conclusions and remarks

A detailed environmental study regarding the current management of municipal organic wastes generated in Catalonia (ISc1) and its comparison with a future management scenario (LFD1) fulfilling the landfill directive has been performed by means of a LCA.

The main conclusion of this study is that the environmental performance of the different OFMSW treatment technologies should be included as a decision criterion in waste management planning. The new LFD1 scenario decreases the environmental impact in 5 out of 6 impact categories (GWP, ADP, AP, EUP and OLDP) and only POP shows a higher impact.

Sensitivity analysis shows that an improvement of landfill gas collection is of utmost importance in order to decrease the GWP. Also a detailed study regarding fugitive emissions in AD installations is necessary, AD installations are the most suitable technologies from an environmental point of view, on the other hand fugitive emissions could increase the GWP up to 31 % if this technology is widely used in new treatment facilities.

It is worth to remark that the data used in this work has been previously obtained in in-situ studies of treatment plants placed in the same geographical area avoiding some of the uncertainty related to the characteristics of the waste treated.

It should also be highlighted that there are economical and social constraints regarding waste management planning that have not been considered in this study. The cost of the different treatment options, the importance of the waste collection system and the source selection process as well as social acceptance required for home composting implementation are extremely important factors.

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## 6. References

Agència de Residus de Catalunya (Catalan Waste Agency): Statistics of Waste Generation in Catalonia 2012. http://www20.gencat.cat/docs/arc/Home/Consultes%20i%20tr%C3%A0mits%20-%20nou/Estadistiques/Estadistiques%20de%20residus%20municipals/recollida_selectiva_2012.pdf. Accessed 3 july 2014

Agència de Residus de Catalunya (Catalan Waste Agency): PRECAT 2014-2020. http://participacioarc.cat/docs/PRECAT20/PRECAT20.pdf. Accessed 3 july 2014

Agència de Residus de Catalunya (Catalan Waste Agency): Summary of the Municipal Waste Management Program http://www20.gencat.cat/docs/arc/Home/Ambits%20dactuacio/Planificacio/progremic_resum.pdf. Accessed 9 April 2013.

Amlinger F, Peyr S, Cuhls C. 2008. Greenhouse gas emissions from composting and mechanical biological treatment. Waste Manage. Res. 26:47–60.

Andersen JK, Boldrin A, Christensen TH, Scheutz C. 2011. Mass balances and life cycle inventory of home composting of organic waste. Waste Manage. 31:1934–1942.

Bernstad A, la Cour Jansen J. 2011. A life cycle approach to the management of household food waste - A Swedish full-scale case study. Waste Manage. 31:1879-1896.

Blengini GA. 2008. Using LCA to evaluate impacts and resources conservation potential of composting: A case study of the Asti District in Italy. Resour. Conserv. Recy. 52:1373-1381.

Boldrin A, Andersen JK, Christensen TH. 2011. Environmental assessment of garden waste management in the Municipality of Aarhus, Denmark. Waste Manage. 31:1560-1569.

Cadena E, Colón J, Sánchez A, Font X, Artola A. 2009. A methodology to determine gaseous emissions in a composting plant. Waste Manage. 29:2799-2807.

Cadena E. 2009. Environmental impact analysis at full-scale OFMSW biological treatment plants. Focus on gaseous emissions. PhD Thesis, Universitat Autònoma de Barcelona, Bellaterra, Spain. http://ddd.uab.cat/pub/tesis/2009/tdx-1027110-003459/ec1de1.pdf. Accessed 15 October 2012.

Colón J, Martínez-Blanco J, Gabarrell X, Rieradevall J, Font X, Artola A, Sánchez A. 2009. Performance of an industrial biofilter from a composting plant in the removal of ammonia and VOCs after material replacement. J. Chem. Technol. Biotechnol. 84:1111-1117.

Sostenipra, 2013. Carbon footprint tool of waste management in Europe ($CO_2$ZW). http://co2zw.eu.sostenipra.cat/. Accessed 3 july 2014.

Colón J, Martínez-Blanco J, Gabarrell X, Artola A, Sánchez A, Rieradevall J, Font X. Environmental assessment of home composting. Resour. Conserv. Recy. 54:893–904.
Colón J, Cadena E, Pognani M, Barrena R, Sánchez A, Font X, Artola A. 2012. Determination of the energy and environmental burdens associated with the biological treatment of source-separated Municipal Solid Wastes. Energy Environ. Sci. 5:5731-5741.
Council of the European Union. 1999. Directive 1999/31/EC, on the Landfill of Waste. http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31999L0031:EN:NOT. Accessed 16 October 2012.
De Feo G, Malvano C. 2009. The use of LCA in selecting the best MSW management system. Waste Manage. 29:1901-1912.
Diaz R, Warith M. 2006. Life-cycle assessment of municipal solid wastes: Development of the WASTED model. Waste Manage. 26:886-901.
Emery A, Davies A, Griffiths A, Williams K. 2007. Environmental and economic modeling: A case study of municipal solid waste management in Wales. Resour. Conserv. Recy. 49:244–263.
European Commission. 2008. Green Paper on the Management of Bio-waste in the European Union 2008. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2008:0811:FIN:EN:PDF. Accessed 16 October 2012.
Eurostat. 1999. Municipal waste generation and treatment, by type of treatment method. http://epp.eurostat.ec.europa.eu/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=tsdpc240. Accessed 15 October 2012.

Fricke K, Santen H, Wallmann R. 2005. Comparison of selected aerobic and anaerobic procedures for MSW treatment. Waste Manage. 25:799-810.

Guinée JB. 2002. Life Cycle Assessment, an Operational Guide to the ISO Standars. Parts 1, 2 and 3. Ministry of Housing. Spatial Planning and Environment (VROM) and Centre of Environmental Science (CML). Den Haag and Leiden, The Netherlands.

Intergovernmental Panel on Climate Change, IPPC. 2006. IPCC Guidelines for National Greenhouse Gas Inventories, http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.htm. Accessed 9 April 2013.

Interrnational Organisation for Standardisation. 2006. ISO 14040–14044. Environmental Management, Life Cycle Assessment. International Standard, Geneva, Switzerland.

Iriarte A, Gabarrell X, Rieradevall J. 2009. LCA of selective waste collection systems in dense urban areas. Waste Manage. 29:903-914.

Kaplan PO, Ranjithan SR, Barlaz MA. 2009. Use of Life-Cycle Analysis to support solid waste management planning for Delaware. Environ. Sci. Technol. 43:1264-1270.

Kirkeby JT, Birgisdottir H, Hansen TL, Christensen TH, Bhander GS, Hauschild M. 2006. Environmental assessment of solid waste systems and technologies: EASEWASTE. Waste Manage. Res. 24:3-15.

Komilis DP, Ham RK. 2000. Life Cycle Inventory and Cost Model for Mixed Municipal and Yard Waste Composting. USEPA, 2000. https://mswdst.rti.org/docs/Compost_Model_OCR.pdf. Accessed, April 2013.

Komilis DP, Ham RK, Park JK. 2004. Emission of volatile organic compounds during composting of municipal solid wastes. Water Res. 38:1707-1714.

Liamsanguan C, Gheewala SH. 2008. LCA: A decision support tool for environmental assessment of MSW management systems. J. Environ. Manage. 87:132-138.

Marchand M, Aissani L, Mallard P, Béline F, Réveret JP. 2013. Odour and Life Cycle Assessment (LCA) in Waste Management: A Local Assessment Proposal. Waste Biomass Valor. 3:603-617.

Martínez-Blanco J, Muñoz P, Antón A, Rieradevall J. 2009. Life cycle assessment of the use of compost from municipal organic waste for fertilization of tomato crops. Resour. Conserv. Recy. 53:340-351.

Martínez-Blanco J, Colón J, Gabarrell X, Font X, Sánchez A, Artola A, Rieradevall J. 2010. The use of life cycle assessment for the comparison of biowaste composting at home and full scale. Waste Manage. 30:983–994.

Møller J, Boldrin A and Christensen TH. 2009. Anaerobic digestion and digestate use: accounting of greenhouse gases and global warming contribution. Waste Manage & Res. 27:813-824.

Oficina Catalana del Canvi Climàtic. 2014. Catalunya i els objectius de reducció d'emissions de gasos amb efecte d'hivernacle. http://www20.gencat.cat/docs/canviclimatic/Home/Campanyes%20i%20comunicacio/Publicacions/Publicacions%20de%20lOficina%20Catalana%20del%20Canvi%20Climatic/Quart%20informe%20de%20progres%20a%20Catalunya/Quart%20Informe%20de%20Progres_Febrer2014.pdf. Accessed July, 2014.

Orzi V, Cadena E, D'Imporzano G, Artola A, Davoli E, Crivelli M, Adani F. 2010. Potential odour emission measurement in organic fraction of municipal solid waste during anaerobic digestion: Relationship with process and biological stability parameters. Bioresource Technol. 101:7330–7337.

Özeler D, Yetiş Ü, Demirer GN. 2006. Life cycle assessment of municipal solid waste management methods: Ankara case study. Environ. Int. 32:405-411.

Pagans E, Font X, Sánchez A. 2006. Emission of volatile organic compounds from composting of different solid wastes: Abatement by biofiltration. J. Haz. Mat. 131:179-186.

Skordilis A. 2004. Modelling of integrated solid waste management systems in an island. Resour. Conserv. Recy. 41:243-254.

Smet E, Van Langenhove H, De Bo I. 1999. The emission of volatile compounds during the aerobic and the combined anaerobic/aerobic composting of biowaste. Atmos. Environ. 33:1295-1303.

Sonesson U, Dalemo M, Mingarini K, Jönsson H. 1997. ORWARE – A simulation model for organic waste handling systems. Part 2: Case study and simulation results. Resour. Conserv. Recy. 21:39-54.

Villalba G, Bueno S, Gabarrell X, Font X. 2012. GHG contribution of sorting plants and mechanical biological treatment plants – Case study of Catalonia, Spain. In Lavagnolo, C. (Ed.) A Glance at the World. Waste Manage. 32:1999–2002.

Table 1. Municipal solid waste generated in Catalonia during year 2012 (ARC 2014).

| Catalonia municipal waste | | |
|---|---|---|
| Total MSW | **3,731** | Gg |
| Total mixed municipal solid waste | **2,274** | Gg |
| Total source selected municipal solid waste | **1,457** | Gg |
| Biodegradable solid waste | 488 | Gg |
| Pruning | 99 | Gg |
| OFMSW (15 % improper material) | 384 | Gg |
| OFMSW (improper free) | 326 | Gg |
| Home composting | 5 | Gg |
| Paper and cardboard | 318 | Gg |
| Glass | 169 | Gg |
| Packaging | 135 | Gg |
| Others (bulky material, oil, tires, textile, bateries, inert material, WEEE, etc.) | 347 | Gg |

Table 2. Organic waste generated and treated in Catalonia during year 2012 (ARC 2014).

| Catalonia municipal organic waste | | |
|---|---|---|
| Biodegradable solid waste generation | 1,317 | Gg |
| Pruning | 99 | Gg |
| Total OFMSW generated | 1,218 | Gg |
| Total source selected OFMSW treated | 326 | Gg |
| Home composting | 5 | Gg |
| Total OFMSW not source selected | 887 | Gg |
| Landfilled without treatment* | 344 | Gg |
| Incineration* | 103 | Gg |
| Treated in MBT plants* | 440 | Gg |

*39 % of mixed MSW corresponded to OFMSW (ARC 2014)

Table 3. Inventory data obtained from the installations considered in this study (AD: anaerobic digestion; CT: in-vessel composting; AWC: aerated windrows composting; TWC: turned windrows composting, HC: home composting) previously published in (Colón et al. 2012). AWB (aerated and turned windrows with gaseous emissions treatment) data have been theoretically calculated.

| Facility | | AD & MSW-AD | CT & MSW-CT | AWC | TWC | HC | AWB |
|---|---|---|---|---|---|---|---|
| Inputs | MJ electricity | 166.32 | 770.4 | 235.8 | 33.41 | 33.77 | 354.8 (119)* |
| | MJ electricity self-generation | 167.04 | 0 | 0 | 0 | 0 | 0 |
| | L diesel | 3.64 | 2.66 | 9 | 5.33 | 0 | 9 |
| | Total MJ (electricity + diesel) | 472.26 | 871.9 | 579.24 | 236.8 | 33.77 | 698.24 |
| Outputs | kg $NH_3$ | 0.23 | 0.11 | 2 | 8.63 | 0.84 | 0.2 (90)** |
| | Kg VOC | 0.86 | 0.75 | 6.22 | 5.7 | 0.56 | 1.87 (70)** |
| | kg $N_2O$ | 0.035 | 0.085 | 0.076 | 0.251 | 0.676 | 0.076 (0)** |
| | kg $CH_4$ | 2.39 | 0.15 | 1.68 | 4.37 | 0.16 | 1.51 (10)** |
| | $m^3$ biogas | 98.9 | n/a | n/a | n/a | n/a | n/a |
| | MJ electricity | 550.08 | n/a | n/a | n/a | n/a | n/a |

* Value in brackets is the surplus of energy needed for the implementation of a gas treatment in AWB plants

** Values in brackets are the gas treatment removal efficiency considered in AWB plants

Table 4. Impact potentials determined for OFMSW treatment plants representative of the treatment technologies implemented in Catalonia (Colón et al. 2012).

| Treatment technology | Gaseous emissions treatment | Impact potentials | | | | | |
|---|---|---|---|---|---|---|---|
| | | GWP | ADP | AP | EUP | ODP | POP |
| | | (kg $CO_2$ eq $y^{-1}$) | (kg Sb eq $y^{-1}$) | (kg $SO_2$ eq $y^{-1}$) | (kg $PO_4^{3-}$ eq $y^{-1}$) | (kg CFC-11 eq $y^{-1}$) | (kg $C_2H_4$ eq $y^{-1}$) |
| Anaerobic Digestion (AD & MBT-AD) | Wet scrubber + biofilter | 45.2 | -0.16 | 0.16 | 0.07 | -2.67E-07 | 0.36 |
| In-vessel composting (CT & MBT-CT)* | Wet scrubber + biofilter | 105.1 | 0.6 | 0.9 | 0.1 | 5.48E-06 | 0.35 |
| Aerated windrows composting (AWC) | No | 123 | 0.43 | 3.75 | 0.72 | 4.52E-06 | 2.59 |
| Aerated windrow composting with biofiltration (AWB) (theoretical) | Biofilter | 182 | 0.56 | 1.59 | 0.21 | 6.41E-06 | 1.22 |
| Turned windrows composting (TWC) | No | 196 | 0.14 | 14 | 3.03 | 2.37E-06 | 2.38 |
| Home composting (HC) | No | 209 | 0.04 | 1.4 | 0.3 | 3.05E-07 | 0.23 |

* Average value from Colón et al., 2012 & Martínez-Blanco et a., 2010

GWP: global warming potential; ADP: abiotic depletion potential; AP: acidification potential; EUP: eutrophication potential; ODP: ozone layer depletion potential; POP: photochemical oxidation potential

Table 5. Total and partial impact results for Scenario ISc1:

| | Number of installations | Treated OFMSW (Gg $y^{-1}$) | GWP (t $CO_2$ eq $y^{-1}$) | ADP (t Sb eq $y^{-1}$) | AP (t $SO_2$ eq $y^{-1}$) | EUP (t $PO_4^{3-}$ eq $y^{-1}$) | OLDP (t CFC-11 eq $y^{-1}$) | POP (t $C_2H_4$ eq $y^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| Source-selected OFMSW | | | | | | | | |
| Anaerobic Digestion (AD) | 5 | 196 | 8,859 | -31.4 | 31.4 | 13.7 | -5.23E-05 | 70.6 |
| In-vessel composting (CT) | 7 | 85 | 8,934 | 51.2 | 76.3 | 6.2 | 4.65E-04 | 30.0 |
| Aerated windrows composting (AWC) | 3 | 25 | 3,075 | 10.8 | 93.8 | 18.0 | 1.13E-04 | 64.8 |
| Turned windrows composting (TWC) | 7 | 20 | 3,920 | 2.8 | 280.0 | 60.6 | 4.74E-05 | 47.6 |
| Home composting (HC) | 20,000 | 5 | 1,045 | 0.2 | 7.0 | 1.5 | 1.53E-06 | 1.2 |
| Collection and transport | | 326 | 13,333 | 86.7 | 59.7 | 11.9 | 2.00E-03 | 2.3 |
| Non Source-selected OFMSW (from mixed MSW) | | | | | | | | |
| Anaerobic Digestion (MSW-AD) | 1 | 41 | 1,853 | -6.6 | 6.6 | 2.9 | -1.09E-05 | 14.8 |
| In-vessel composting (MSW-CT) | 10 | 399 | 41,939 | 240.6 | 358.1 | 29.2 | 2.18E-03 | 140.8 |
| Collection and transport | | 440 | 17,996 | 117.0 | 80.5 | 16.0 | 2.69E-03 | 3.1 |
| Incineration | 4 | | | | | | | |
| Fresh OFMSW | | 103 | 5,044 | 28.4 | 45.4 | 9.1 | 3.09E-04 | 0.8 |
| SS-OFMSW refuses | | 8 | 392 | 2.2 | 3.5 | 0.7 | 2.40E-05 | 0.1 |
| NSS-OFMSW refuses | | 45 | 2,204 | 12.4 | 19.8 | 4.0 | 1.35E-04 | 0.4 |
| Collection and transport of fresh OFMSW | | 103 | 2,834 | 18.4 | 12.7 | 2.5 | 4.24E-04 | 0.5 |
| Transport of SS-OFMSW & NSS-OFMSW refuses | | 0 | | | | | | |
| Sanitary Landfill | 29 | | | | | | | |
| Fresh OFMSW | | 344 | 168,717 | 182.1 | 109.9 | 826.5 | 9.57E-04 | 35.6 |
| SS-OFMSW refuses | | 30 | 14,714 | 15.9 | 9.6 | 72.1 | 8.35E-05 | 3.1 |
| NSS-OFMSW refuses | | 65 | 31,880 | 34.4 | 20.8 | 156.2 | 1.81E-04 | 6.7 |
| Biostabilized material | | 100 | 1,203 | 52.9 | 31.9 | 240.3 | 2.78E-04 | 10.4 |
| Collection and transport of fresh OFMSW | | 344 | 25,628 | 162.7 | 116.3 | 24.0 | 3.85E-03 | 4.2 |
| Transport of SS-OFMSW & NSS-OFMSW refuses | | 95 | 1,267 | 8.2 | 5.7 | 1.1 | 1.90E-04 | 0.2 |
| Transport of biostabilized materials | | 110 | 1,334 | 8.7 | 6.0 | 1.2 | 2.00E-04 | 0.2 |
| Total environmental impact ($t_{IC}$ $y^{-1}$) | | 1218 | 3.56E+05 | 9.98E+02 | 1.37E+03 | 1.50E+03 | 1.4E-02 | 4.37E+02 |
| Total environmental impact ($t_{IC}$ $Gg^{-1}$ OFMSW) | | 1218 | 2.92E+02 | 8.19E-01 | 1.13E+00 | 1.23E+00 | 1.16E-05 | 3.59E-01 |

Table 6: Comparison of the environmental impacts for the seven scenarios considered (ISc2–ISc8). Initial ISc1 is considered as the base scenario (100% of contribution of each category), whereas the rest of scenarios are normalized to this base scenario. Impact

| Impact category | Units ($Gg^{-1}$ OFMSW) | Initial Scenario ISc1 | Sensitivity analysis for other scenarios (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | ISc2 | ISc3 | ISc4 | ISc5 | ISc6 | ISc7 | ISc8 |
| GWP | (t $CO_2$ eq $y^{-1}$) | 3.56E+05 | 82 | 94 | 105 | 109 | 136 | 98 | 95 |
| ADP | (t Sb eq $y^{-1}$) | 9.98E+02 | 60 | 86 | 100 | 100 | 106 | n.a. | n.a. |
| AP | (t $SO_2$ eq $y^{-1}$) | 1.37E+03 | 80 | 93 | 100 | 100 | 106 | n.a. | n.a. |
| EP | (t $PO_4^{3-}$ eq $y^{-1}$) | 1.50E+03 | 96 | 99 | 100 | 100 | 100 | n.a. | n.a. |
| OLDP | (t CFC-11 eq $y^{-1}$) | 1.41E-02 | 34 | 77 | 100 | 100 | 114 | n.a. | n.a. |
| POP | (t $C_2H_4$ eq $y^{-1}$) | 4.37E+02 | 98 | 99 | 101 | 102 | 108 | n.a. | n.a. |

ISc2: Transport not included
ISc3: Average distance from collection points to SS-OFMSW treatment facilities is 5 km and the average distance to landfills is 10 km
ISc4: methane fugitive emissions (5 %) are included in AD & MSW-AD treatment plants
ISc5: methane fugitive emissions (10 %) are included in AD & MSW-AD treatment plants
ISc6: landfill biogas collection decreased to 17 %
ISc7: Compost is used as organic amendment
ISc8: Compost and biostabilizaed are used as organic amendment
n.a: not analyzed

Table 7. Total and partial impact results for Scenario LFD1.

| | Treated OFMSW ($Gg\ y^{-1}$) | GWP ($t\ CO_2\ eq\ y^{-1}$) | ADP ($t\ Sb\ eq\ y^{-1}$) | AP ($t\ SO_2\ eq\ y^{-1}$) | EUP ($t\ PO_4^{3-}\ eq\ y^{-1}$) | OLDP ($t\ CFC\text{-}11\ eq\ y^{-1}$) | POP ($t\ C_2H_4\ eq\ y^{-1}$) |
|---|---|---|---|---|---|---|---|
| Source-selected OFMSW | | | | | | | |
| Anaerobic Digestion (AD) | 525 | 22,600 | -80.0 | 80.0 | 35.0 | -1.34E-04 | 180.0 |
| In-vessel composting (CT) | 135 | 13,139 | 75.4 | 112.2 | 9.1 | 6.84E-04 | 44.1 |
| Aerated windrows composting (AWB) | 45 | 14,742 | 45.4 | 128.8 | 17.0 | 5.19E-04 | 98.8 |
| Home composting (HC) | 25 | 5,225 | 1.0 | 35.0 | 7.5 | 7.63E-06 | 5.8 |
| Collection and transport | 705 | 28,835 | 187.5 | 129.0 | 25.7 | 4.315E-03 | 4.9 |
| Non Source-selected OFMSW (from mixed MSW) | | | | | | | |
| Anaerobic Digestion (MSW-AD) | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.00E+00 | 0.0 |
| In-vessel composting (MSW-CT) | 487 | 51,189 | 293.6 | 437.1 | 35.6 | 2.67E-03 | 171.9 |
| Collection and transport | 487 | 19,918 | 129.5 | 89.1 | 17.7 | 2.98E-03 | 3.4 |
| Incineration | | | | | | | |
| Fresh OFMSW | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.00E+00 | 0.0 |
| SS-OFMSW refuses | 15 | 735 | 4.1 | 6.6 | 1.3 | 4.50E-05 | 0.1 |
| NSS-OFMSW refuses | 50 | 2,449 | 13.8 | 22.0 | 4.4 | 1.50E-04 | 0.4 |
| Collection and transport of fresh OFMSW | 103 | 2,834 | 18.4 | 12.7 | 2.5 | 4.24E-04 | 0.5 |
| Transport of SS-OFMSW & NSS-OFMSW refuses | 0 | | | | | | |
| Sanitary Landfill | | | | | | | |
| Fresh OFMSW | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.00E+00 | 0.0 |
| SS-OFMSW refuses | 56 | 27,466 | 29.6 | 17.9 | 134.6 | 1.56E-04 | 5.8 |
| NSS-OFMSW refuses | 72 | 35,313 | 38.1 | 23.0 | 173.0 | 2.00E-04 | 7.5 |
| Biostabilized material | 121 | 1,456 | 64.1 | 38.7 | 290.7 | 3.37E-04 | 12.5 |
| Collection and transport of fresh OFMSW | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.00E+00 | 0.0 |
| Transport of SS-OFMSW & NSS-OFMSW refuses | 95 | 1,267 | 8.2 | 5.7 | 1.1 | 1.90E-04 | 0.2 |
| Transport of biostabilized materials | 121 | 1,614 | 10.5 | 7.2 | 1.4 | 2.42E-04 | 0.3 |
| Total environmental impact ($t_{IC}\ y^{-1}$) | 1218 | 2.29E+05 | 8.39E+02 | 1.14E+03 | 7.57E+02 | 1.28E-02 | 5.36E+02 |
| Total environmental impact ($t_{IC}\ Gg^{-1}$ OFMSW) | 1218 | 1.88E+02 | 6.89E-01 | 9.40E-01 | 6.21E-01 | 1.05E-05 | 4.40E-01 |

Table 8: Comparison of the environmental impacts for the nine scenarios considered (ISc2–ISc10). Scenario LFD1 is considered as the base scenario (100% of contribution of each category), whereas the rest of scenarios are normalized to this base scenario. Impact

| Impact category | Units ($Gg^{-1}$ OFMSW) | Initial Scenario | Sensitivity analysis for other scenarios (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LFD1 | LFD2 | LFD3 | LFD4 | LFD5 | LFD6 | LFD7 | LFD8 | LFD9 | LFD10 |
| GWP | (t $CO_2$ eq $y^{-1}$) | 2.29E+05 | 75 | 101 | 108 | 118 | 131 | 117 | 96 | 93 | 88 |
| ADP | (t Sb eq $y^{-1}$) | 8.39E+02 | 56 | 105 | 128 | 100 | 100 | 101 | 97 | n.a. | n.a. |
| AP | (t $SO_2$ eq $y^{-1}$) | 1.14E+03 | 78 | 104 | 120 | 100 | 100 | 101 | 97 | n.a. | n.a. |
| EP | (t $PO_4^{3-}$ eq $y^{-1}$) | 7.57E+02 | 93 | 100 | 100 | 100 | 100 | 100 | 100 | n.a. | n.a. |
| OLDP | (t CFC-11 eq $y^{-1}$) | 1.28E-02 | 35 | 101 | 114 | 100 | 100 | 102 | 95 | n.a. | n.a. |
| POP | (t $C_2H_4$ eq $y^{-1}$) | 5.36E+02 | 98 | 100 | 100 | 102 | 103 | 101 | 99 | n.a. | n.a. |

LFD2: Transport not included
LFD3: New designed SS-OFMSW facilities uses CT technology instead of AD technology
LFD4: All the extra SS-OFMSW is treated by means of CT technology (AD treats the same amount as in ISc1)
LFD5: methane fugitive emissions (5 %) are included in AD treatment plants
LFD6: methane fugitive emissions (10 %) are included in AD treatment plants
LFD7: landfill biogas collection decreased to 17 %
LFD8: landfill biogas collection increased up to 60 %
LFD9: Compost is used as organic amendment
LFD10: Compost and biostabilizaed are used as organic amendment
n.a: not analyzed

**Figure Captions**

**Fig 1** Waste treatment scenarios considered in this study. 1a) Current scenario (ISc1) and 1b) future scenario fulfilling the European landfill directive (LFD1).

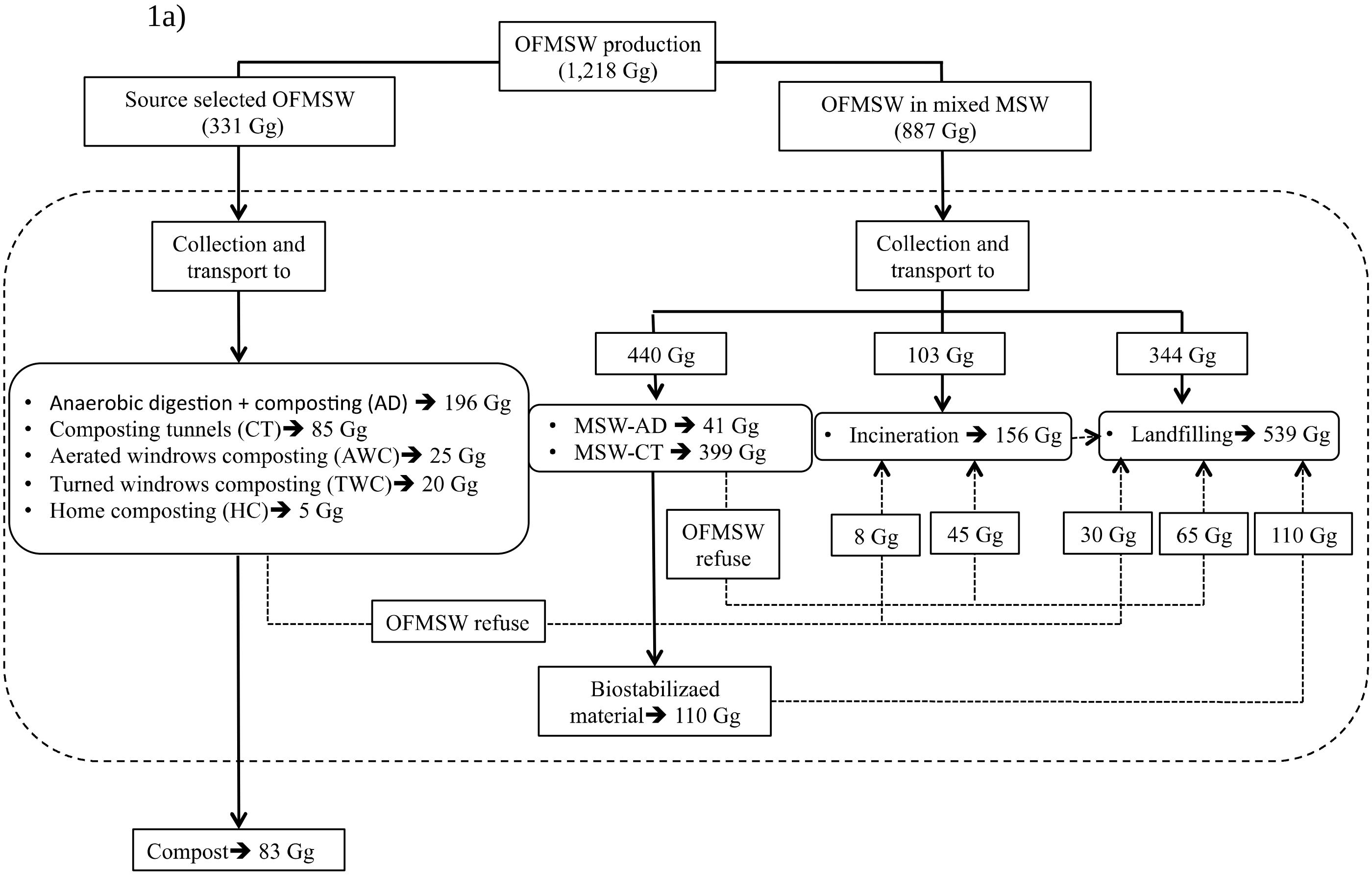
**Fig 2** Fig 2.a Contribution (in percentage) of the items considered in scenario ISc1 to its total environmental impact. Figure 3b, contribution (in percentage) of the items considered (transport excluded) in scenario ISc1 to its total environmental impact. Impact categories: GWP, global warming potential; ADP, abiotic depletion potential; AP, acidification potential; EP, eutrophication potential; OLDP, ozone layer depletion potential; POP, photochemical oxidation potential; CED, cumulative energy demand.

**Fig 3** Fig 3.a Contribution (in percentage) of the items considered in scenario LFD1 to its total environmental impact. Figure 3b, contribution (in percentage) of the items considered (transport excluded) in scenario LFD1 to its total environmental impact. Impact categories: GWP, global warming potential; ADP, abiotic depletion potential; AP, acidification potential; EP, eutrophication potential; OLDP, ozone layer depletion potential; POP, photochemical oxidation potential; CED, cumulative energy demand.

**Fig 4** Comparison of the total environmental impacts of the two proposed scenarios: ISc1 and LFD1.

Figure 1

1a)




1b)

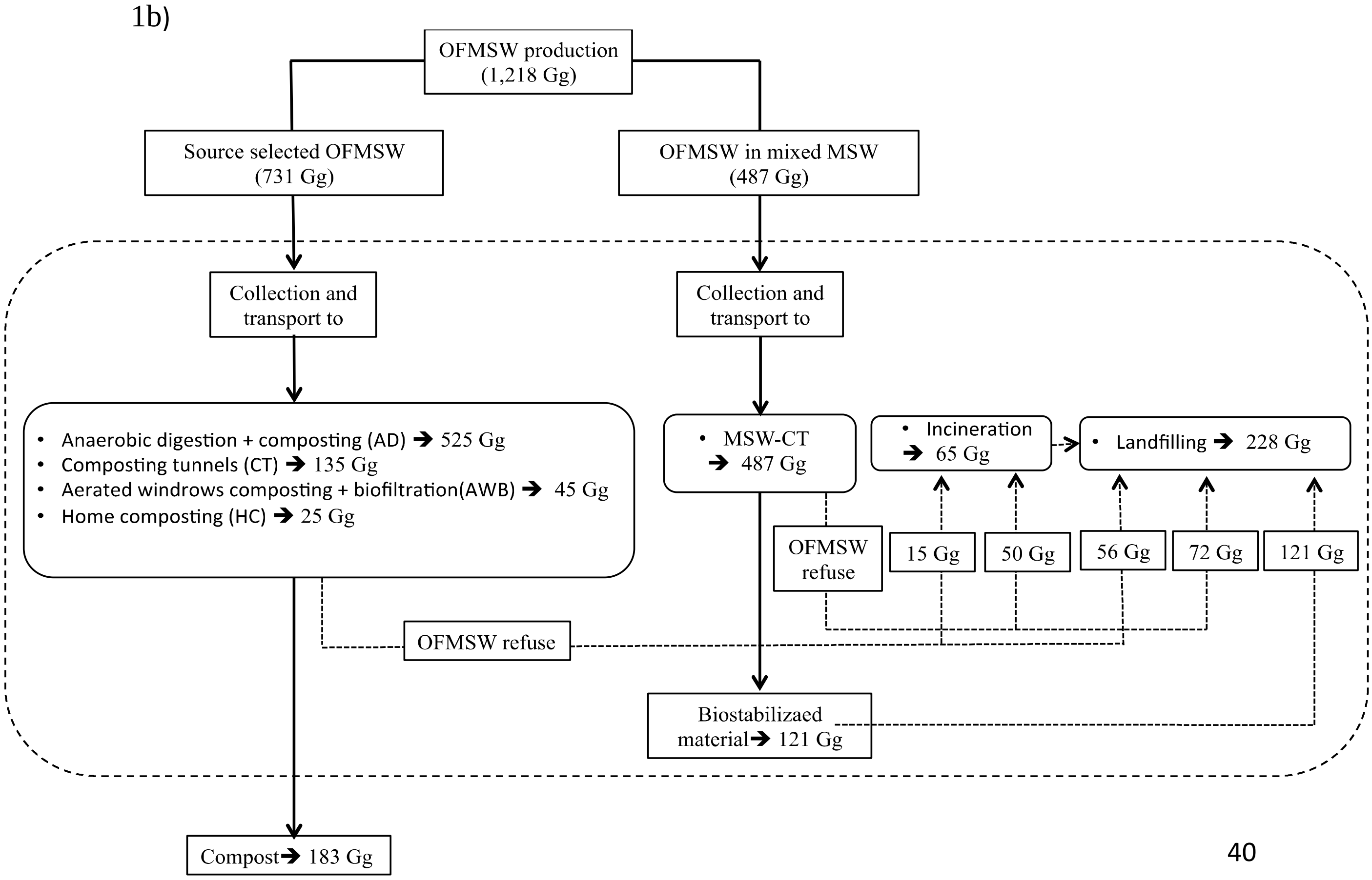
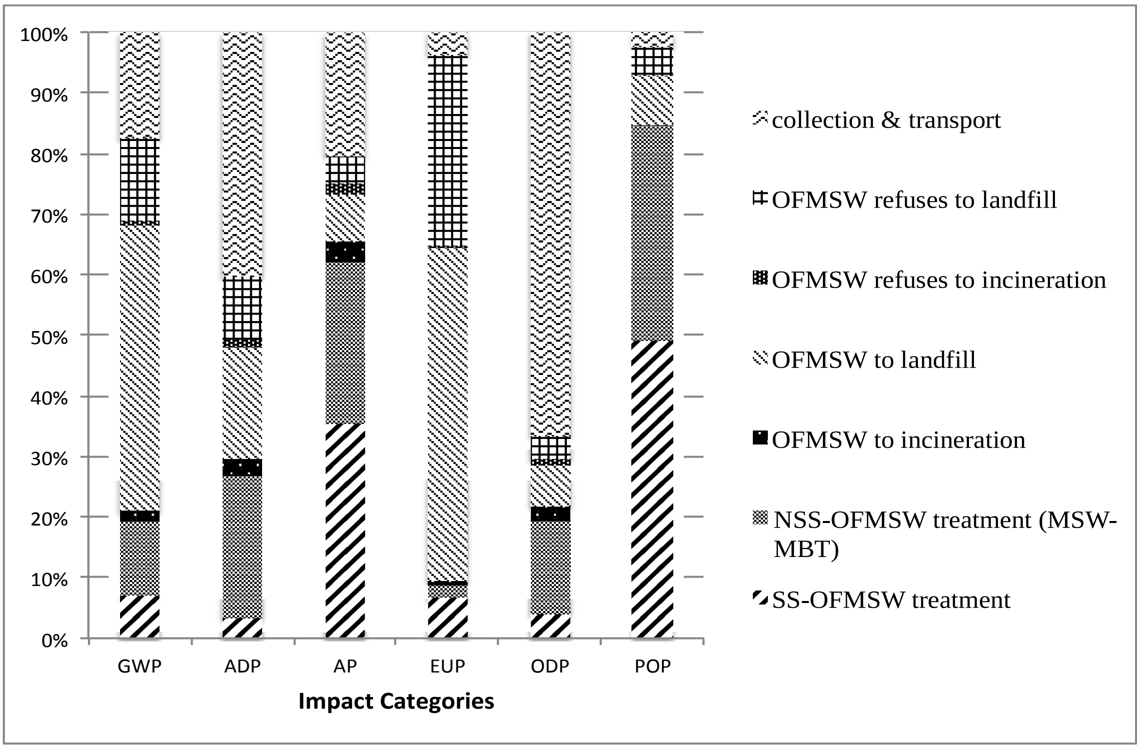


Figure 2

2.a)




2.b)

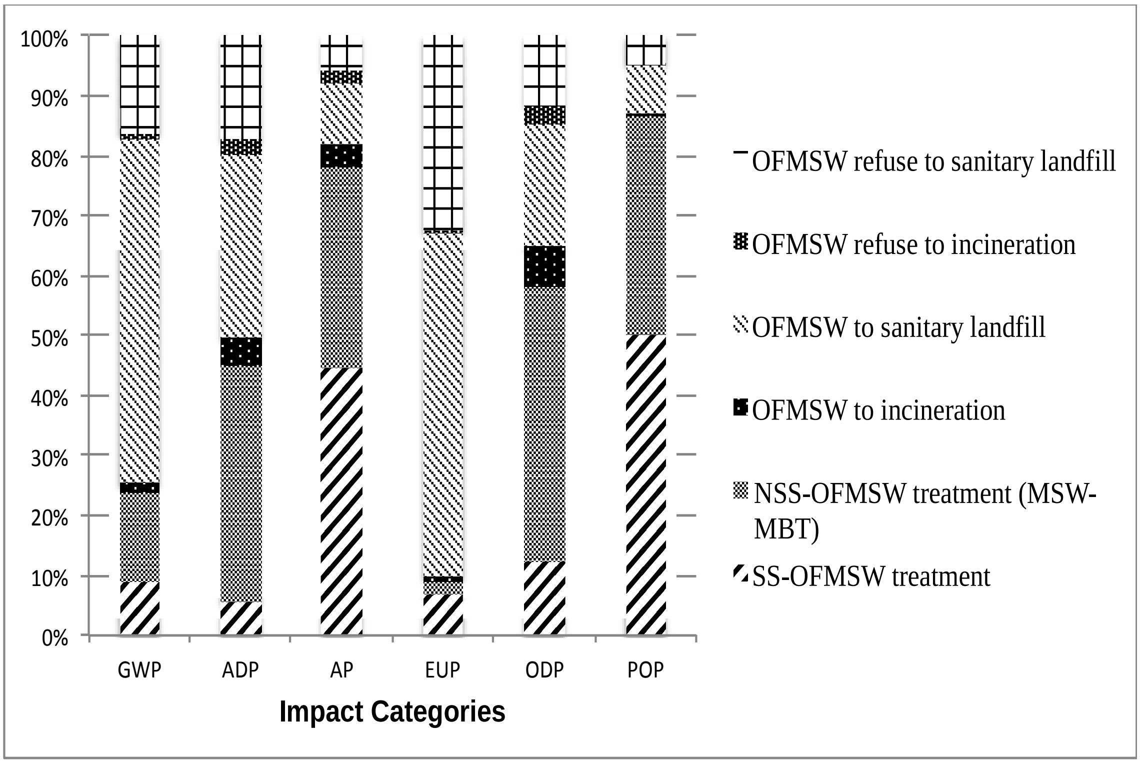
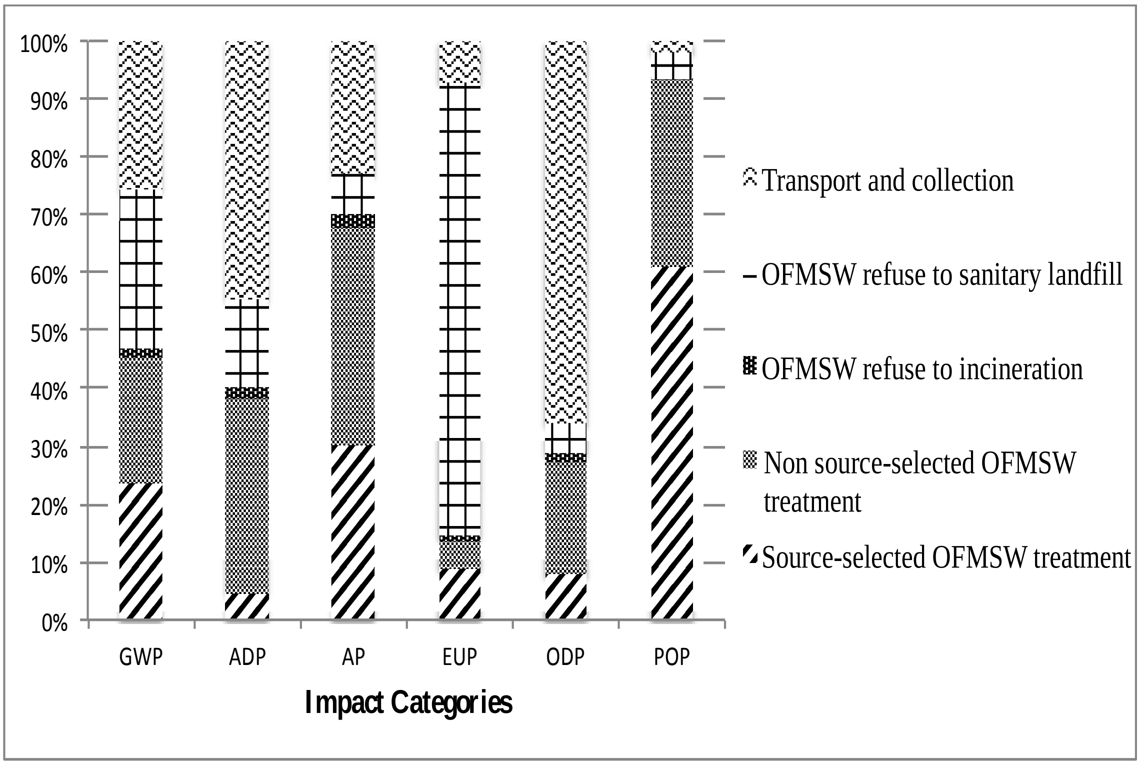


Figure 3

3.a)




3.b)

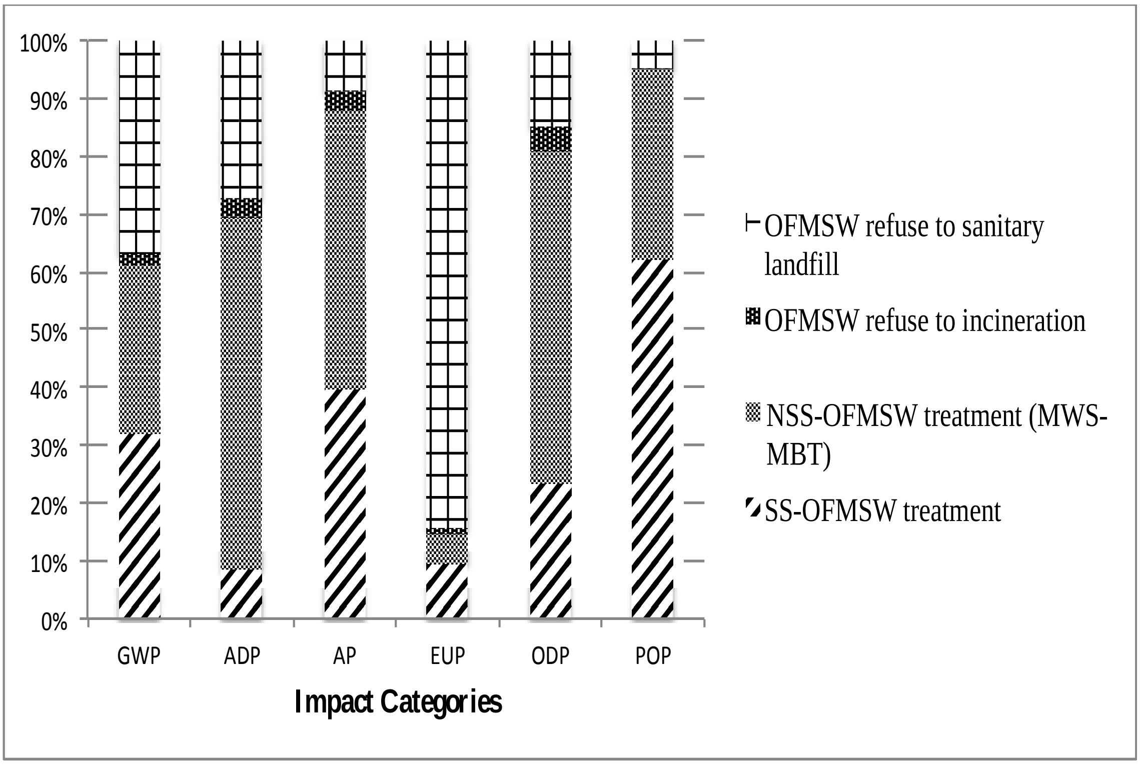
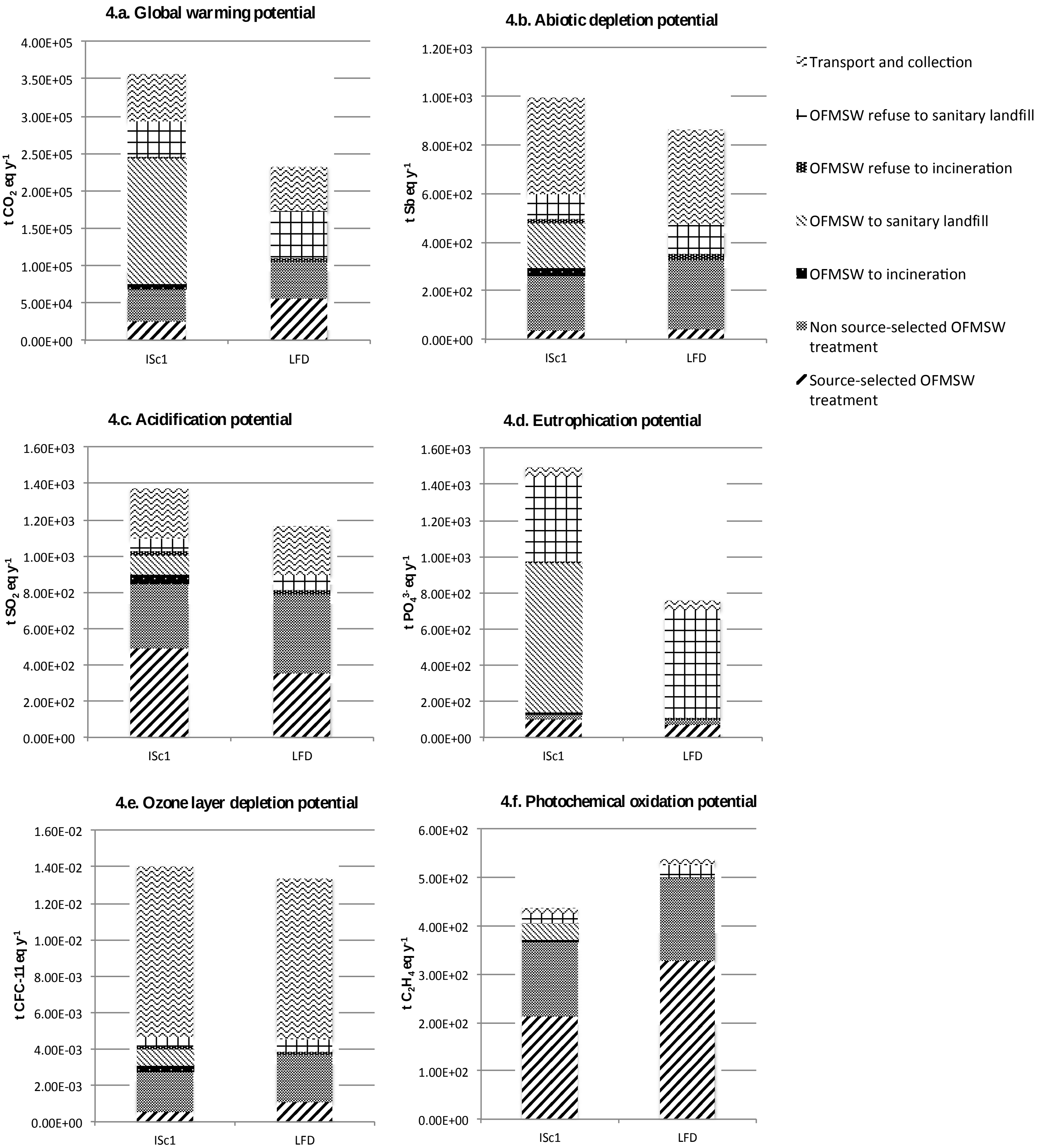


Figure 4.


4.a. Global warming potential
t $CO_2$ eq $y^{-1}$
4.00E+05
3.50E+05
3.00E+05
2.50E+05
2.00E+05
1.50E+05
1.00E+05
5.00E+04
0.00E+00
ISc1
LFD
4.b. Abiotic depletion potential
t Sb eq $y^{-1}$
1.20E+03
1.00E+03
8.00E+02
6.00E+02
4.00E+02
2.00E+02
0.00E+00
ISc1
LFD
Transport and collection
OFMSW refuse to sanitary landfill
OFMSW refuse to incineration
OFMSW to sanitary landfill
OFMSW to incineration
Non source-selected OFMSW treatment
Source-selected OFMSW treatment
4.c. Acidification potential
t $SO_2$ eq $y^{-1}$
1.60E+03
1.40E+03
1.20E+03
1.00E+03
8.00E+02
6.00E+02
4.00E+02
2.00E+02
0.00E+00
ISc1
LFD
4.d. Eutrophication potential
t $PO_4^{3-}$ eq $y^{-1}$
1.60E+03
1.40E+03
1.20E+03
1.00E+03
8.00E+02
6.00E+02
4.00E+02
2.00E+02
0.00E+00
ISc1
LFD
4.e. Ozone layer depletion potential
t CFC-11 eq $y^{-1}$
1.60E-02
1.40E-02
1.20E-02
1.00E-02
8.00E-03
6.00E-03
4.00E-03
2.00E-03
0.00E+00
ISc1
LFD
4.f. Photochemical oxidation potential
t $C_2H_4$ eq $y^{-1}$
6.00E+02
5.00E+02
4.00E+02
3.00E+02
2.00E+02
1.00E+02
0.00E+00
ISc1
LFD