Impact of different management options for organic waste: a life cycle analysis

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Abstract

Different management options of the organic fraction (OF) generated in a given urban area were analyzed by a life cycle assessment (LCA) approach for different source segregation (SS) intensities ranging from 0% up to 52%. Best management options for the different SS values were represented by the presence of incineration for processing the amount of OF remaining in the residual waste (ROF). The introduction of aerobic treatment and/or of anaerobic digestion (AD) for processing the SSOF leads to relevant environmental impact reduction even if the difference between the two options results quite negligible. A noticeable role is played by the amount of renewable energy recoverable from AD. An increase of about 50% of the biogas generated from the AD in the scenario with SS=52% with incineration of ROF leads to a global environmental gain.

Keywords: Aerobic Treatment, Anaerobic Digestion, Energy recovery, Incineration, Life Cycle Assessment, Landfill, Organic Fraction, Source Segregate collection.

1. Introduction

Municipal solid waste (MSW) is composed by a wide range of materials and product among which a prominent role is played by the organic fraction (OF). As reported by several authors (Buttol et al., 2007; Cherubini et al., 2009; Di Maria et al., 2013a; Di Maria and Micale, 2013; Iriarte et al., 2009) OF can represent from 15 $\%ww^{-1}$ up to more than 40% ww^{-1} of the whole MSW. If not properly managed OF can lead to relevant environmental threat due to gaseous and liquid emissions arising from biological reactivity and leaching phenomena (De Gioannis et al., 2009; Di Maria et al., 2013b; Pohland and Kim, 1999). Biodegradable materials, as the OF, disposed of without adequate pre-treatments makes landfill one of the most relevant site for anthropogenic greenhouse gas (GHG) generation. In the EU-15 landfill contributes for about 3% to the whole GHG emission (EEA, 2011). This is a consequence of degradation process leading to the generation of gasses as CH_4 and N_2O, along with CO_2, with a very high GHG potential, respectively of 21 and 310 times higher than CO_2 (Desideri et al., 2003).

Furthermore, landfill leachate usually shows values of COD >10,000 mgL^{-1}, of NH_4 > 500 mgL^{-1} and contains other pollutant substances as a consequence of leaching phenomena occurring for the OF and for other biodegradable materials.

For these reasons the EU Landfill Directive of April 1999 (99/31/EC) imposes a mandatory stepwise reduction of the biodegradable fraction going directly to landfill of 25%, 50% and 65% respectively by 2006, 2009 and 2016.

Possible solution for reducing these problems can be represented by incineration or by mechanical and biological treatments aimed to reducing residual biological reactivity of the MSW before dispose off (De Gioannis et al., 2009; Di Maria et al. 2013a; Frike et al., 2005; Komilis et al., 1999). Anyway one of the most effective approach for diverting MSW from landfill is represented by source segregated collection (SS) aimed to recovery and recycling operation. In particular SS OF can be biologically processed for the production of an high quality organic fertilized exploitable for agricultural use.

Even if the SS followed by recycling and recovery operations, represents and effective way for reducing the environmental burden of MSW management, it involves different social, economical and environmental aspects strongly influenced by local conditions. This causes a significant debate on what could be the most sustainable waste management configuration able to match all these questions. In other word what could be the most sustainable compromise among SS intensity, recovery, recycling and direct disposal operation of MSW.

Di Maria and Micale (2013) investigate the effects of SS intensity on fuel consumption and collection costs related to an existing waste management system of an Italian urban area. Results shows that higher is the SS intensity higher are both fuel consumptions and collection costs even these findings results strongly influenced by the waste collection vehicles (WCV) and crew optimization. Similar results were also obtained by other authors analyzing waste collection costs (Dogan and Duleyman, 2003; Chose et al., 2006; Tavares et al., 2009).

Concerning pre-treatment and disposal options Cherubini et al. (2009) shows that mechanical and biological treatment (MBT), with solid recovered fuel (SRF) production represent the best environmental options compared to landfilling and incineration. If SRF is not present, Buttol et al., (2007) demonstrate that for the Bologna (Italy) management district the best option for residual MSW after SS collection is represented by incineration.

Di Maria et al. (2013a) shows that for waste management scenarios based on MBT and landfill with energy recovery, without SRF production, an excessive MSW bio-stabilization is not the best solution reducing the benefits of renewable energy production from landfill gas.

Concerning the organic waste management, Blengini (2008) evaluates by a life cycle assessment (LCA) approach the impact and resource conservation potential of composting. Results show that composting in more energy consumption than landfill but a remarkable energy saving is due to chemical fertilizer avoidance. Similarly Lundie and Peters (2005) make an LCA analysis of several food waste management options. Also in this case composting shows the best environmental figures.

These data shows that there is a lack of information about the integrated management of OF including different SS intensities and consequent pre-treatment, recovery and disposal options.

In the present study, starting from and existing Italian urban waste management scenario (Di Maria and Micale, 2013) different management option have been evaluated by an LCA approach. Particular attention has been focused on the energy generation options from the OF.

2. Matherials and Methods

2.1 LCA methodology and scope

When applying LCA to waste management, the classical cradle-to-grave approach has to be modified to gate-to-cradle or gate-to-grave (Blengini et al., 2012), depending if recycling or disposal operations are analyzed. In accordance with the methodology of ISO 14040 (2006), LCA was used to assess the environmental impact and the environmental gains concerning the different SS intensities, recovery and disposal operations considered in this work. A system not in expansion was assumed. The functional unit was a single ton of OF (Table 1) generated and hence managed in the urban area considered, whereas the LCA model was implemented by the SimaPro8 software (Prè Consultants, 2013). In agreement with Rigamonti et al. (2009), who analyzed a similar aspect for a northern Italian area, the characterization method chosen was the CML2 (CML, 2001). In general the inventory adopted was chosen among the those available in the econinvent database v2.2 (Hischier et al., 2010). Specific modifications and adjustments were introduced for all those processes for which real and/or experimental data were available. The Italian scenario was assumed for all the energetic aspects, including electricity and fuel, avoided or consumed. Italy imports about 2% of its entire electrical energy needs from surrounding States, whereas 19% and 43% is produced, respectively, by coal and natural gas used for fuelling thermo-electrical power plants. The remaining fraction is produced mainly by hydroelectric, other fossil fuels and renewable sources (*i.e.* about 36%).

2.2 Inventory analysis

The single tonne of OF generated in the urban area considered can be processed in different ways (Fig. 1) (Table 2). The SSOF can be processed exclusively by composting or by anaerobic digestion (AD) followed by composting. In both cases the treatment goal is represented by material recovery for organic fertilizer production. The amount of OF remaining in the residual waste (ROF) can undergo different treatment and disposal operations. The base option for ROF management is direct landfilling. Another option is incineration with energy recovery followed by ash and slag disposal. Alternatively the ROF can be processed in a MBT facility aimed at material recovery and waste stabilization before final disposal in a landfill. Energy required for treatments and recycling were taken both from literature and from the full-scale facility operating in the considered area or in similar areas (Table 3).

Component	**% ww^{-1}**
Glass	7.00
Textile	1.50
Plastics	12.6
Organic Fraction	**20.3**
Paper and cardboard	35.5
Wood	3.60
Metals	6.50
Others	12.7

Table 1. Municipal solid waste composition

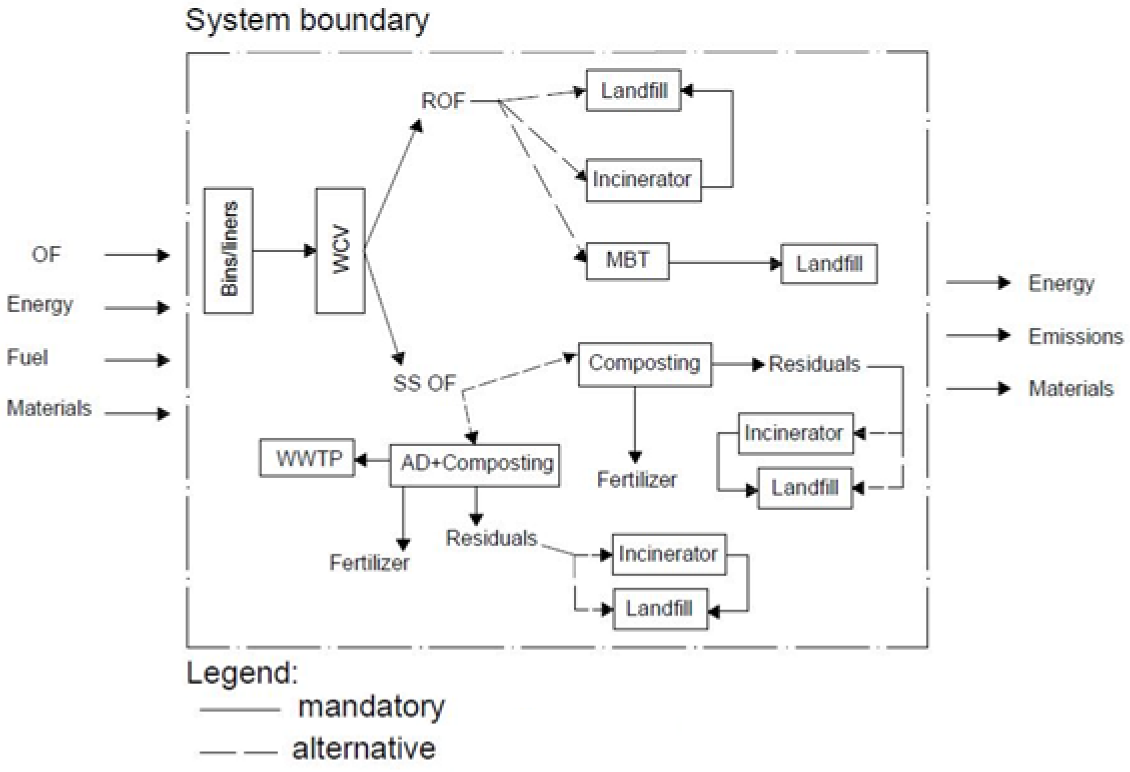

Figure 1. system boundary.

SS (%)	Scenario N°	MBT	Incineration	Landfill	Compost	AD
0	0.1			ROF		
0	0.2		ROF	ROF[a]		
0	0.3	ROF		ROF[b]		
25	25.1			ROF		
25	25.2		ROF	ROF		
25	25.3	ROF		ROF		
30/35/52	30/35/52.1			ROF	SSOF	
30/35/52	30/35/52.2		ROF	ROF[a]	SSOF	
30/35/52	30/35/52..3	ROF		ROF[b]	SSOF	
30/35/52	30/35/52.6			ROF	SSOF	SSOF
30/35/52	30/35/52.7		ROF	ROF[a]	SSOF	SSOF
30/35/52	30/35/52.9	ROF		ROF[b]	SSOF	SSOF

Legend: a=ash and slag after incineration – b=after screening and biostabilization in MBT

Table 2. Organic fraction management options after collection for different SS intensities.

Operation	OF	Energy	Reference
MBT	ROF		
Electricity		33 kWh tonne^{-1}	Plant
Composting	SSOF		
Electricity[a]		11.8 kWh tonne^{-1}	Hischier et al., 2010

Legend: "Plant"=data measured on full-scale facilities – a=per tonne of compost

Table 3. Energy consumption for MBT of ROF and composting of SSOF.

2.3 Selection of environmental indicators

Environmental indicators were chosen using a top-down approach (Blengini et al., 2012) according to ISO (2006) recommendations. These indicators are internationally recognized and widely exploited in LCA analysis (Belngini et al., 2012; Iriarte et al., 2009; Wang et al., 2012). In particular they are: Global Warming Potential at 100 years (GWP100), Acidification Potential (AP), Eutrophication Potential (EP); Photochemical Oxidation Potential (POP); Ozone Layer Depletion Potential (OLDP), Abiotic Depletion Potential (ADP), Human Toxicity Potential (HTP) and Terrestrial Ecotoxicity Potential (TEP) (Table 4). These impact indicators were used to evaluate the global impact by the CML2 method. Evaluation of the global impact of each scenario can be performed by adding the respective impact category after the normalization and weighting procedure. The impact category was divided by the corresponding normalization factor and multiplied by the associated weight (Table 4). Weights choche represent a crictical step in LCA analysis. The weights adopted in this work were those suggested by Guinée et al. (2001).

Impact category	Unit	Normalization factor	Unit	Weight
GWP100	kgCO$_2$ eq.	4.15E+ 13	kgCO$_2$ eq./a	2.4
AP	kgSO$_2$ eq.	3.22E+ 11	kgSO$_2$ eq./a	1.3
EP	kgPO$_4$ eq.	1.32E +11	kgPO$_4$ eq.	1
POCP	kgC$_2$H$_2$ eq.	9.69E+ 10	kgC$_2$H$_2$ eq./a	0.8
HTP	kg1,4-DB eq.	5.71E+ 13	kg1,4-DB eq./a	1.1
TEP	kg1,4-DB eq.	2.69E+ 11	kg1,4-DB eq./a	0.4
ADP	kgSb eq.	1.56E+ 11	kgSb eq./a	0.01
OLDP	kgCFC-11 eq.	5.15E+ 8	kgCFC-11 eq./a	1

Table 4. Environmental impact category, weight and normalization factors (CML, 2001; Guinée et al., 2001).

2.4 Collection system

The first component of the waste management system was the collection activity. The scenario considered was an existing urban area consisting of seven different collection routes (Di Maria and Micale, 2013). In the reference configuration (*i.e.* SS=0%), total driving distance was about 190 km/day and the average daily MSW production was about 35.8 tonnes. The resident population was about 24,000 inhabitants. Starting from the existing collection configuration Di Maria and Micale (2013) performed different analyses by varying the SS intensity. Number, volume and positions of bins and liners were evaluated for each SS value together with number, size and fuel consumption of WCV (Table 5). Bin production, maintenance and substitution every 5 years were taken into consideration (Rives et al., 2010), whereas liners were considered biodegradable only for the SSOF and single use. Similarly, on the basis of the respective size, WCV construction and maintenance was included assuming an average life of 10 years. ROF was collected commingled with residual MSW exploiting large size WCV from 22 m^3 to 24 m^3. SSOF was collected with small size vehicles from 3 m^3 to 6 m^3. Fuel consumption per tonne of ROF collected results quite constant. Detected variation are mainly a consequence of the optimization of the amount of waste loaded by the WCV. Similar results were found for the SSOF collection. For both ROF and SSOF the scenario with a SS=52% allow an optimal WCV loading leading to a maximum values in fuel consumption $Ltonne^{-1}$ (Di Maria and Micale, 2013).

SS (%)	**OF (%ww^{-1})**	**Bin (L)**	**CP**	**Distance (km day^{-1})**	**Fuel consumption (L tonne^{-1})**
0	ROF (100)	2,400-1,000	342	193	2.98
25	ROF (100)	2,400-1,000	342	193	2.65
30	ROF (75)	2,400-1000	342	193	2.78
	SSOF (25)	120	342	193	6.00
35	ROF (75)	2,400-1,000-1,200	342	193	2.97
	SSOF (25)	120	342	193	5.60
52	ROF (11)	2,400-1,000-770	342	193	2.39
	SSOF (89)	Liner	1066	208	3.34

Table 5. Bin size, collection points (CP), daily distance and fuel consumption per each tonne of ROF and SSOF collected for different SS intensities.

2.5 Mechanical and biological treatment

MBT plays an important role in different EU areas as an alternative to incineration. Even with lower effectiveness, MBT can reduce MSW reactivity and mass before disposal. MBT can also extract from MSW recyclable and recoverable materials (Di Maria, 2012).

In particular MSW undergoes mechanical processing such as shredding, screening and metal sorting, aimed at separating the ROF from the other recyclable material and components with higher calorific value. The ROF is then biologically pretreated to reduce its reactivity and mass before being disposed of. Reduction in waste biological reactivity also reduces landfill gas (LFG) generation (Di Maria et al., 2013b). In this work the energy necessary for processing one tonne of ROF in an existing MBT facility has been considered (Table 3).

2.6 Composting and anaerobic digestion

Composting is a complex biological process leading to significant bio-chemical and physical transformations of the OF. Furthermore, the production of a high quality organic fertilizer also requires physical and mechanical treatments for refining this material in order to comply with the required legal and commercial standards. The concentration of impurities such as plastics, metals and other bulky components have to be lower than the established limits imposed by the single EU states. Furthermore aerobic process induce a partial biological gasification of the organic matter along with a considerable moisture reduction. This means that even if SS is conducted with a high efficiency, the mass of compost produced is usually significantly lower than the treated mass of SSOF. This difference can be greatly influenced by local situations, collection methods and also by the technology used. For this reason a mass balance was performed on composting facility operating in the collection area, which processes about 4,500 tonnes year^{-1} of SSOF. Considering 1 tonne of SSOF at the plant inlet, for the period ranging from 2006 to 2010, results show that 600 kg are process losses, 270 kg are process waste and 130 kg are high quality compost. For each tonne of high quality compost, avoided production of mineral nutrients as N, K_2O and P_2O_5 was assumed to be 23 kg, 9 kg and 9.5 kg, respectively. The ecoinvent v2.2 inventory for composting was hence adjusted on the basis of these data and on the basis of data reported in Table 3.

The same amount of compost produced per tonne of SSOF was assumed in the scenario with AD. The ecoinvent v2.2 data base inventory for AD was modified concerning the energy production and liquid digestate treatment. In a previous study on the AD of the SSOF arising from the same collection area there was an energy potential of about 220 kWh SSOFtonne^{-1} (Di Maria, 2012). Due to the impossibility of agronomic exploitation of the liquid fraction of the digestate in the area considered, its purification in a waste water treatment plant (WWTP) was considered. In accordance with Bolzonella et al. (2006) the amount of liquid to be processed in the WWTP was assumed to be 0.45 m^3 SSOFtonne^{-1}.

2.7 Landfill and Incineration

With the exception of the scenarios in which an incinerator was used, the landfill was assumed to be equipped with an energy recovery system. For this reason the inventory available in the ecoinvent v2.2 database (Hischier et al., 2010) concerning landfill of bio-degradable waste EU27 and internal combustion engine production and maintenance was implemented with flare and internal combustion engine emissions (Table 6) (Beylot et al., 2013; Di Maria et al., 2013a).

In accordance with Di Maria et al. (2013a) the amount of electrical energy recoverable was assumed to be 62 kWh tonne^{-1} for untreated MSW. For waste streams arising from mechanical and biological treatments the amount of electrical energy recoverable was assumed to be 33.5 kWh tonne^{-1}. These data were based on results obtained assuming that the amount of collected landfill gas was 50% of the global generated. Electrical energy production of other landfilled waste streams arising from other treatments was disregarded. The model adopted for the ROF incineration was the same available in ecoinvent v2.2 related to the disposal of bio-waste to municipal incinerator. The amount of electrical energy recovered was about 42 kWh ROFtonne^{-1}.

Emission	**Value**		**Unit**	**Reference**
	Flare	**Internal combus. eng.**		
NO_x	0.631	11.60	g Nm^{3}CH$_4^{-1}$	USEPA (2008)
CO	0.737	8.460	g Nm^{3}CH$_4^{-1}$	
PM	0.238	0.232	g Nm^{3}CH$_4^{-1}$	
Dioxins/furans	6.7E-9	-	g Nm^{3}CH$_4^{-1}$	
SO_x (as SO_2)	80	100	g tonne MSW^{-1}	NSCA (2002)
HCl	40	9	g tonne MSW^{-1}	
HF	8	10	g tonne MSW^{-1}	
Gas NMVOCs	99.23	97.15	% removal	USEPA (2008)

Table 6. Default inventory data for the emissions for the flare and internal combustion engine.

3. Result and discussion

Main results shows that, in general the higher is the SS intensity the lower is the system impact (Figs. 2 and 3). Even the collection activities shows in general an increased energy and materials consumptions (Table 5) the environmental incidence of this phase on the global management of the single tonne of OF results marginal. This finding was in accordance with results obtained by other authors (Assamoi and Lawryshyn, 2012; Blengini, 2008). Some mayor differences were found in the impact indicators values depending on the management option adopted after the collection phase.

Due to the absence of landfill gas emissions and to the lower energy consumptions, incinerator of ROF results to be the best option for reducing the GWP (Fig. 2). In this cases, the presence of aerobic and anaerobic treatments for the SSOF in the management scenarios with SS higher than 25% leads to a slight increase of the GWP. This is a consequence of the amount of material and energy necessary for the aerobic and anaerobic facility construction and management along with the considered energetic scenario (*i.e.* Italy). In fact, the high percentage of fossil fuel exploited for the Italian energy generation affects in a relevant way the amount of equivalent CO_2 emissions per kWh.

For the scenarios adopting landfill or MBT, as the amount of SSOF rise the GWP results reduced even the larger energetic consumption of MBT generate always the higher equivalent CO_2 emissions. For the higher SS intensities the scenario adopting AD shows higher GWP compared to the adoption of aerobic treatment alone. The main reason of this phenomenon can be found in the energetic consumption due to the need of composting and WWTP for solid and liquid digestate treatment along with the higher incidence of the energetic consumption for AD facility construction per SSOF tonne.

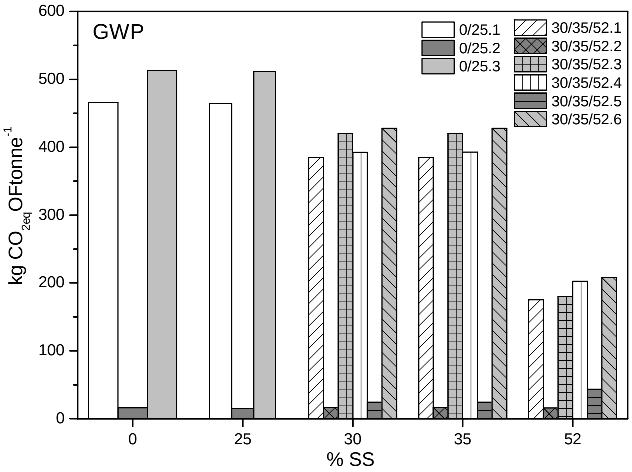

Figure 2. Global warming potential (GWP) for different management scenario of the single tonne of organic fraction.

Positive role of incineration related to GWP is also reported by Assamoi and Lawryshyn (2012) for managing residual MSW resulting from SS collection even at a noticeably higher cost. Similar results were obtained by Moberg et al. (2005) in comparing incineration with landfill for paper disposal. Results show that GWP associate with incineration option has a significant lower value if compared to the landfill one.

Similar considerations can be done also for the EP and POP (Fig. 3) with the respective exception: the presence of the AD together with incineration leads to a reduction of the EP as the SS intensity increases whereas the POP for the same scenarios has an opposite trend. In the first case the reason is mainly due to the reduction of the release of nutrients in the environment and in the second case the reason is represented by the increased amount of gaseous hydrocarbons leakage. For the AP incineration and landfill shows quite similar values in all the analyzed scenarios. MBT shows the higher incidence concerning AP that in any case results reduced both for higher SS intensities and for the adoption of AD. In the scenario 52.5 the synergic effects of incineration and AD lead to an environmental gain concerning the acidification potential.

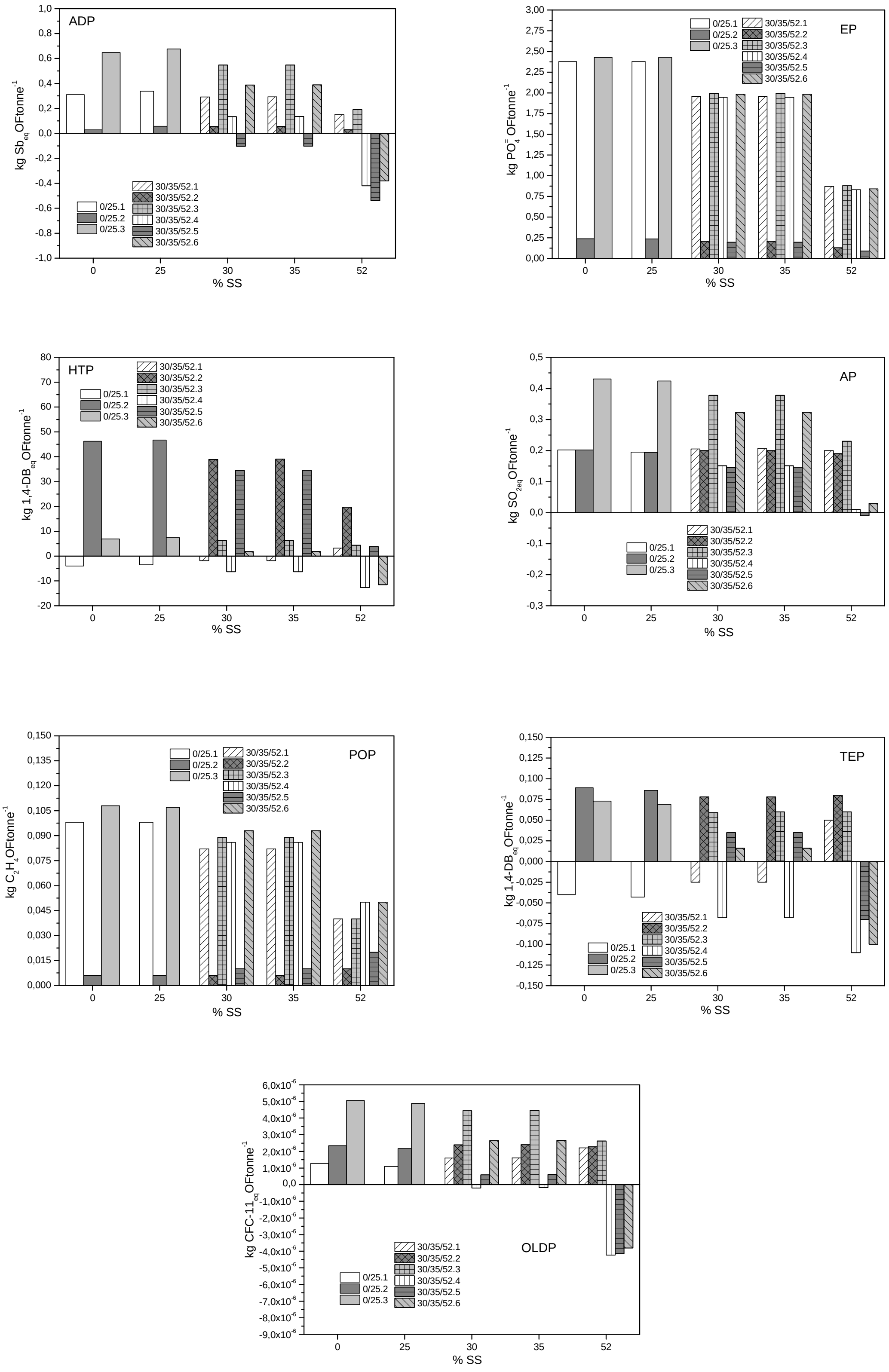

Figure 3. Abiotic depletion potential (ADP), eutrophication potential (EP), human toxicity potential (HTP), acidification potential (AP), photochemical oxidation potential (POP), terrestrial ecotoxicity potential (TEP) and ozone layer depletion potential (OLDP) for the different management scenario of the single tonne of organic fraction.

Positive effects of the combination of incineration and AD are also detected for the ADP. In this case starting from a SS=30% the above mentioned treatments combination lead to rising environmental benefits mainly as a consequence of fossil fuel consumption avoidance due to renewable energy production. Also for this impact category the exploitation of the landfill along with the MBT is the worst solutions.

The higher impact for TEP is represented by incineration followed by MBT. The increase of SS intensity affects marginally this figure. In the scenarios with SS from 0% to 35% landfill ad landfill with AD represents an environmental gain. This is mainly a consequence of the large amount of renewable energy generable per tonne of managed OF. For SS=52% landfill without AD represent TEP impact as a consequence of the reduced amount of ROF disposed (*i.e.* lower energy recovery) and of the increased energy consumption due to the aerobic treatment of the SSOF. At the same SS intensity, the adoption of AD for processing the SSOF leads to environmental gain for all the considered management combinations from 52.4 to 52.6. The OLDP results lower for the scenarios with landfill and maximum for the scenarios with MBT. OLDP results quite constant for all the scenarios without AD. The presence of AD combined with landfill leads to impact reduction for the scenarios with SS=30% and 35%. For the scenario with 52% the presence of the AD leads to environmental benefits for all the management combinations analyzed.

Landfill and landfill with AD represents environmental benefits also for the HTP whereas, as expected, the worst solution is represented by incineration.

Global impact (Fig. 4) shows that the increase of SS intensity has noticeable positive effects for the scenarios with landfill and MBT whereas the improvement achievable for the scenario adopting the incineration appears quite negligible. Another interesting result is represented by the quite similar values for the global impact for the scenarios with SS=0% and 25%, and for the scenarios with SS=30% and 35%. Decisive improvements in the management of the OF can be achieved only for higher SS intensity values. For SS=52% the adoption of aerobic treatment and of AD combined with aerobic treatment shows practically similar global impact values. These results are in accordance with the ones proposed by other authors.

In analyzing possible waste management options in the Peoloponnese region in Greece Antonopoulos et al. (2013) finds that the maximum environmental benefits can be achieved for the scenarios adopting incineration together with the anaerobic digestion. Abduli et al. (2011) performs an LCA analysis of solid waste management strategies in Tehran comparing the landfill to the landfill with composting for the organic fraction. Results show that the last solution is the one with the lower impact. Blengini (2008) demonstrate for a given management district that composting requires about 20% more energy than landfill and that in the OF recovery process for fertilizer production has a relevant impact is due to bags exploited for the collection.

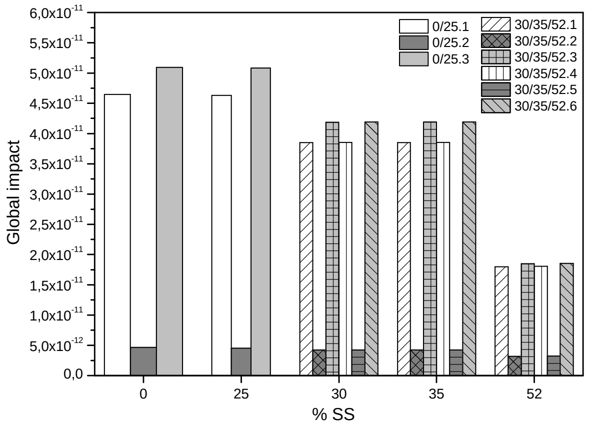

Figure 4. Global impacts for the different OF management scenarios.

Considering the relevant role played by the energy consumption a sensitivity analysis was performed on the global impact of the analyzed systems by increasing separately the amount of biogas produced by the AD and by the fraction of landfill gas collected. In particular biogas production was increased respectively of 10%, 30% and 50% whereas the amount of landfill gas collection was increased from the current 50% respectively to 60% and 70% (Di Maria et al., 2013a).

In both cases these improvements leads to an increase in the amount of renewable energy produced. On the basis of the results reported in Figure 4, the analysis was performed only for the scenarios with SS intensity of 30% and 52% for the AD (Fig. 5) and for the scenarios with SS of 0%, 30% and 52% for the landfill gas (Fig. 6).

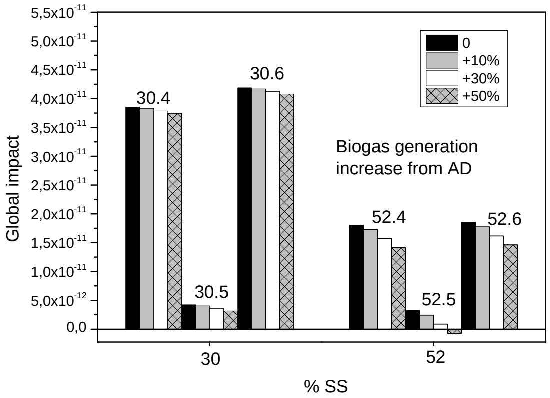

Figure 5. Effect on global impact of the increased amount of biogas produced by the anaerobic digestion.

The energy recoverable from AD passes from the current 220 kWh SSOFtonne^{-1} up to 330 kWh SSOFtonne^{-1}. Consequently, the global impact results reduced for the scenario from 30.4 to 30.6 and from 52.4 to 52.6 (Fig. 5). In particular the larger energy recovery from AD can lead to a global environmental gain for the scenario 52.5 confirming the positive role of the incineration of ROF.

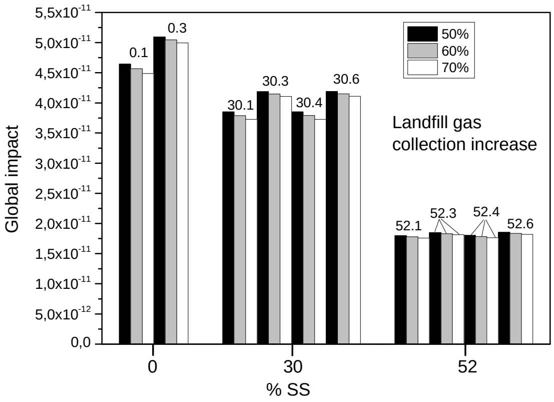

Figure 6. Effect on global impact of the increased fraction of landfill gas collected.

The effect on energy recovery due to an increased amount of collected landfill gas has been assumed to be the same reported by Di Maria et al. (2013a). On the basis of the assumptions made in this work the scenario in which is adopted the incineration is not influenced by this phenomenon. For the other scenarios the effect on the global impact appears less relevant than the one obtainable by the increase of the biogas production from the AD. This is a consequence of the lower amount of landfill gas effectively exploitable for energy recovery per single tonne of ROF compared to the one exploitable per single tonne of SSOF processed in the AD facility.

4. Conclusions

Correct management of the organic fration (OF) of municipal solid waste can lead to significant environmental impact reduction. Direct disposal in landfill, even with energy recovery, or the adoption of preliminary mechanical biological treatment followed by dispose off represents solution with the higher environmental impact. Significant reduction of global impact can be achieved by the adoption of incineration even if this solution shows the higher values for the human toxicity and terrestrial ecotoxicity potentials. The increase in source segregation (SS) intensity aimed to recovery operations represent an effective way for diverting the OF from landfill leading to a proportional reduction of all the impact categories. Best environmental performances were achieved for higher SS intensities in combination with aerobic and anaerobic treatments aimed to the recovery of organic fertilizer along with energy recovery. Main results shows that the global burden represented by aerobic and anaerobic options were quite similar even if the possibility of generating renewable energy leads to environmental gains concerning some specific impact categories.

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