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Life cycle analysis of incineration compared to anaerobic digestion followed by composting for managing organic waste: the influence of system components for an Italian district

Francesco Di Maria · Caterina Micale

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Abstract
Purpose The benefits and environmental burden of two different strategies (incineration vs anaerobic digestion followed by composting) to manage the organic fraction of municipal solid waste were assessed. Particular attention was also focused on system components, including collection, treatment, facility construction, and disposal, as well as the effect of the energetic context. Source segregation intensities considered for the scenario with incineration and with anaerobic digestion followed by composting were respectively of 0 and 52 %.
Methods The analysis was performed by an LCA approach, and the impact was assessed by the CML method. The functional unit was a single ton of organic waste generated in the area considered. System boundaries were expanded to include the differences in waste collection and multi-functionality waste treatments. Existing databases were retrieved, also adopting experimental data for the waste management area considered.
Results and discussion Overall, the scenario with the highest rate of source segregation of organic waste, using anaerobic digestion followed by composting, gave a lower impact for human and terrestrial toxicity. Concerning the other impacts, incineration gave the maximum benefits. The impact of anaerobic digestion and composting arises mainly from energy consumption, greenhouse gas emissions (i.e., N_2O, VOC), and landfilling of residues. The sensitivity analysis performed by varying the energetic mix of the context confirmed the advantages of incineration of the organic fraction.
Conclusions Incineration of organic waste leads to maximum environmental benefits compared to anaerobic digestion and composting. Furthermore, anaerobic digestion and composting was characterized by high gaseous emissions with high greenhouse gas potential even if the production of organic fertilizer gave some benefits concerning the avoided exploitation of mineral resources. The impact due to the collection phase and facility construction was quite limited and in some cases negligible.

Keywords Aerobic treatment · Anaerobic digestion · Energy recovery · Incineration · Life cycle assessment · Organic fraction · Source segregate collection

1 Introduction

1.1 Background of the study

Among the different components of municipal solid waste (MSW), if not properly managed, the organic fraction (OF) is one of the most relevant, both in terms of quantity and of potential pollutant emissions (Di Maria et al. 2013a). Depending on the intensity of source segregation (SS) and on the features of the collection area, OF can represent from 15 up to 40 % *w/w* of the whole MSW generated (Buttol et al. 2007; Cherubini et al. 2009; Di Maria et al. 2013a; Di Maria and Micale 2013). The EU Landfill Directive of April 1999 (99/31/EC) imposes a mandatory stepwise reduction of the biodegradable fraction going directly to landfills of 25, 50, and 65 %, respectively, by 2006, 2009, and 2016. For this reason, specific strategies have been implemented to manage OF. Recovery strategies based on organic fertilizer production give environmental credits associated with avoided mineral fertilizers, but on the contrary, biogenic emissions and energy consumption create an environmental burden (Blengini 2008).

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F. Di Maria (✉) · C. Micale
LAR Laboratory – Dipartimento di Ingegneria, University of Perugia, Via G. Duranti 93, 06125 Perugia, Italy
e-mail: francesco.dimaria@unipg.it

Furthermore, the generation of high quality organic fertilizer requires the implementation of efficient SS of OF, increasing the cost and the impact of the collection activities (Di Maria and Micale 2013; Dogan and Duleyman 2003; Iriarte et al. 2009). Pre-processing the SSOF in an anaerobic digestion (AD) facility, before composting, for renewable energy generation is credited with avoided energy from fossil fuels, but is charged with materials for construction, maintenance, and emissions. Furthermore, the partial stabilization resulting from AD can also reduce the intensity and the length of the successive aerobic treatment. In analyzing different waste management options for the Peoloponnese region in Greece, Antonopoulos et al. (2013) found that AD leads to greater environmental benefits compared to composting. Valerio (2010) reported that the impact of biological treatments of SSOF, such as AD + composting AD + composting, can be reduced if the final compost is used in agriculture. Another possible solution for handling OF is by incineration. OF combustion leads to energy recovery and to a significant reduction in the amount of the biological reactivity of the resulting waste even if at higher cost compared to biostabilization and landfilling (Assamoi and Lawryshyn 2012). Renewable energy from OF incineration can be credited as an environmental gain, whereas plant construction, materials, fossil fuel, and chemicals consumed together with emissions are charged as an environmental burden. Furthermore, in this case, OF can be collected, commingled with other waste, reducing the impact of the collection activity.

1.2 Novelty and aim of the study

In spite of the large number of life cycle assessment (LCA) analyses performed in waste management, there are still many gray areas worthy of investigation. On the basis of more than 200 LCA studies, Laurent et al. (2014a, b) found that there is no definitive agreement as to which is the best waste treatment technology for organic waste. Excluding landfilling, there is great uncertainty between the options of AD + composting and incineration. In this study, using an existing Italian waste management area (Di Maria and Micale 2013), two different OF management strategies were investigated using a LCA approach. A management scenario based on incineration of OF was compared with one adopting AD + composting. The influence of the energy mix of the context considered was also investigated. The aim of the study was to provide administrators and operators useful information about the environmental impact of different options in managing organic waste and to contribute to the discussion as to which is the better solution for OF management.

2 Material and methods

The present LCA study was performed according to ISO 14040 (2006) methodology, also following the indications of the ILCD Handbook guidelines (EC 2010).

2.1 Goal, scope, and context

The environmental impact of the main activities involved in managing OF by incineration and AD + composting were compared. The analysis accounted for all the main steps of OF management were as follows: collection, treatment, and disposal. Data were retrieved from an existing Italian district with 24,000 inhabitants and a MSW generation of 36 tons/day (Di Maria and Micale 2013). Two SS intensities (0 and 52 %) were considered. For SS=0 %, the OF was collected comingled with other municipal waste. HDPE bins with a volume of 770 L were positioned along the roads of the collection routes of the 342 collection points (CP) (Table 1). Waste collection vehicles (WCV) of 18 m^3 loading capacity were used for collecting the waste. The total daily distance driven and fuel consumption were, respectively, 193 km/day and 2.98 L/OF tonne. The OF collected was incinerated, and the slag was landfilled. The door-to-door scheme with bioplastic liners was adopted for OF collection for SS=52 %. In this case, the volumetric loading capacity of the WCV was 6 m^3 and CP=1066. The total daily distance driven and WCV fuel consumption were, respectively, 208 km/day and 3.34 L/OF tonne. SSOF was processed in an AD + composting facility and residues were landfilled. In this case, incineration was not considered viable for the management of residual waste due to their limited amount generated in the considered district when SS=52 %. The scenario with SS=52 % was selected in accordance with the recycling goal of 50 % imposed by the latest EU Waste Framework Directive 2008/98/EC. The foreground of the system varied depending on the management scheme, whereas the background was not significantly influenced by the variation of the foreground. Due to the impossibility of obtaining a complete and specific data set for all the processes and activities included in the study, the inventory was built by retrieving data available from ecoinvent v2.2 (Hischier et al. 2010) and ELCD 2.0 (European Commission 2008). All life cycle strategies prior to the product becoming a waste were not considered assuming a simplification called “zero burden assumption” (Ekvall et al. 2007). System boundaries were expanded to include the different SS intensities and the multi-functionality of the treatments (i.e., system in expansion).

2.1.1 Functional unit

The functional unit (FU) chosen was 1 ton of OF generated in the area considered. Independent of the collection method and

Table 1 WCV, bin size, collection points (CP), daily distance, and fuel consumption per tonne of organic fraction collected for the two scenarios analyzed

SS (%)	Treatment	WCV (m^3)	Bin (L)	CP N°bins/liner	Distance (km/day)	Fuel consumption (L/tonne)
0	Incineration	18	770	342	193	2.98
52	AD + compost	6	Liners	1,066	208	3.34

SS intensity, the OF composition was assumed to be the same in both management schemes. Chemical characterization of the OF is reported in Table 2. These data represent the average values with respect to waste sampled in different periods of the year 2013. The FU is also the reference flow on which the analysis was performed.

2.1.2 Selection of environmental indicators

Environmental mid-point indicators were chosen using a top-down approach (Blengini et al. 2012) according to ISO (2006) recommendations (Table 3). In particular, they were as follows: global warming potential at 100 years (GWP_{100}), acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP), ozone layer depletion potential (OLDP), abiotic depletion potential (ADP), human toxicity potential (HTP), and terrestrial ecotoxicity potential (TEP). To provide an impression of the relative magnitude of the potential impacts and resource consumptions, the impact categories can be normalized using reference information. To compare the results of the present study with other studies reported in the literature, the CML (2001) method was assumed for impact characterization. In fact, even if CML was classified as not always completely in compliance for the determination of the impact categories (EC 2010), it is still the most adopted in previous and recent LCA studies on waste management (Laurent et al. 2014b), in particular for contexts similar to the one analyzed in this work (Rigamonti et al. 2013). Normalization factors, represented by the world emissions related to the year 1995, were used.

2.1.3 Framework of the life cycle inventory modeling and system boundaries

Both incineration and AD + composting significantly transform the OF, generating other products and energy (i.e., multi-functionality). As far as this paper is concerned, the FU and the amount of waste entering the system were considered constant according to the life cycle inventory (LCI) framework. The background of the system (Fig. 1) is as follows: the OF, construction materials, operating and maintenance of facilities, fuel, and electrical energy. In particular, the Italian energetic mix was assumed both for electricity consumed and avoided. Italian electricity grids are connected to surrounding countries and about 13 % of the energy is imported. About 59 % is generated by thermo-electrical power plants fuelled, respectively, by natural gas, 39 % and coal, 20 %. Hydro generates about 12 %, whereas about 9 % is generated by wind and photovoltaic. Geothermal contributes about 1.6 %, the renewable fraction of waste is about 1 %, whereas biogas and biomass contribute, respectively, 1.3 and 1.6 % (TERNA

Table 2 Chemical characterization of the organic fraction (on dry basis)

Parameter	m.u.	Value	Parameter	m.u.	Value
Total organic carbon	g/kg	147	Humidity	% wet basis	60.6
N	g/kg	5.91	Vanadium	mg/kg	N.D.
Arsenic	mg/kg	N.D.	Nickel	mg/kg	N.D.
Mercury	mg/kg	N.D.	Zinc	mg/kg	30.5
Chromium VI	mg/kg	4.45	P	g/kg	7.91
Total copper	mg/kg	13.6	K	g/kg	5.23
Lead	mg/kg	11.7	Al	mg/kg	N.D.
Cadmium	mg/kg	<0.005	Mg	mg/kg	N.D.
Iron	mg/kg	N.D.	Si	mg/kg	N.D.
Boron	mg/kg	N.D.	S	mg/kg	N.D.
Fluorine	mg/kg	N.D.	Tin	mg/kg	N.D.
Selenium	mg/kg	N.D.			

N.D. below the limit of detection

Table 3 Environmental impact categories and normalization factors (CML 2001)

Impact category	Unit	Normalization factor (world 95)	Unit
Global warming potential (GWP_{100})	$kgCO_2$ eq.	4.15E+ 13	$kgCO_2$ eq./a
Acidification potential (AP)	$kgSO_2$ eq.	3.22E+ 11	$kgSO_2$ eq./a
Eutrophication potential (EP)	$kgPO_4$ eq.	1.32E+ 11	$kgPO_4$ eq.
Photochemical ozone creation potential (POCP)	kgC_2H_2 eq.	9.69E+ 10	kgC_2H_2 eq./a
Human toxicity potential (HTP)	kg1.4-DB eq.	5.71E+ 13	kg1,4-DB eq./a
Terrestrial ecotoxicity potential (TEP)	kg1.4-DB eq.	2.69E+ 11	kg1,4-DB eq./a
Abiotic depletion potential (ADP)	kgSb eq.	1.56E+ 11	kgSb eq./a
Ozone layer depletion potential (OLDP)	kgCFC-11 eq.	5.15E+ 8	kgCFC-11 eq./a

2013). In the case of SS=0 %, the OF was transported to the incineration facility (see Section 2.1.7). Slag generated during incineration was assumed to be disposed of by landfilling (see Section 2.1.6). At SS intensity of 52 %, the OF was first processed by AD (see Section 2.1.5). AD generated renewable energy and returned the OF as digestate, which was then mechanically separated into liquid and solid fractions. The solid fraction was processed aerobically to recover an organic fertilizer (DI Maria et al. 2013a), whereas the liquid fraction was processed in a waste water treatment plant (WWTP) because of the impossibility of using this type of liquid digestate as fertilizer in the area considered. On the basis of these management schemes, the foregrounds of the systems were as follows: electrical energy generated by incineration and AD, liquid, solid and gaseous emissions from incineration, AD, composting and WCV operating and maintenance, organic fertilizer.

2.1.4 Waste collection

LCI of bin production, maintenance, and substitution every 5 years were taken into consideration according to Rives et al. (2010), whereas liners were considered biodegradable and single use. Due to their negligible contribution to the impact of the analyzed system, small size bins eventually used by citizens for the domestic storage of the liners containing the organic waste was disregarded. Fifty percent of the biodegradable liners were assumed to be polylactide and 50 % modified starch. Both LCI were retrieved from the ecoinvent database with respect to North American and Italian manufacturers. Similarly, on the basis of the respective size, WCV construction and maintenance was included, assuming an average life of 10 years (Table 4). LCI for WCV was retrieved from the ecoinvent v2.2 database (Hischier et al. 2010), reporting data from a German manufacturer.

2.1.5 AD followed by composting

AD was based on the dry process (Bolzonella et al. 2006), which is the most diffused technological solution for organic waste management (De Baere and Mattheeuws 2010). Based on a previous study on the dry AD of the OF arising from the same collection area, there was a net electrical energy production of about 220 kWh/OF tonne (Di Maria 2012) (Table 5). Except for that required by the digesters, no further recovery of the heat rejected by the co-generators was considered. Both CO_2 generated by the biological process and by bio-methane combustion were considered biogenic. Other relevant GHG

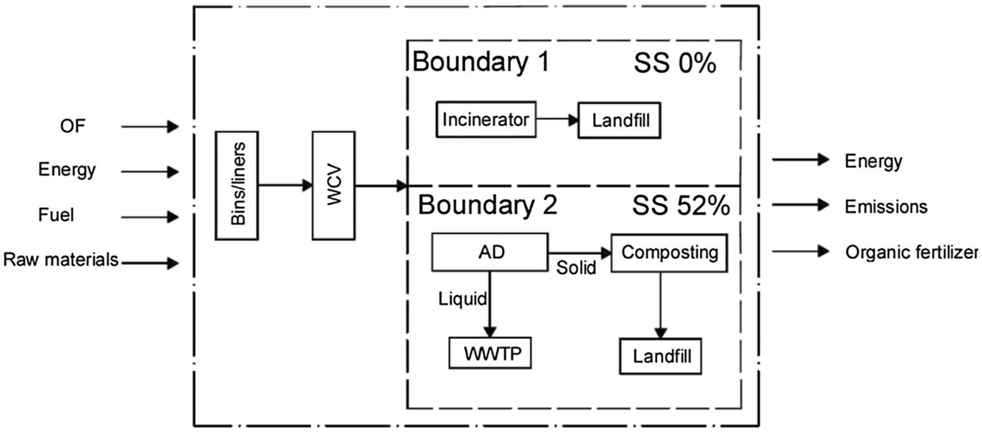


Fig. 1 System boundary

Table 4 LCI of bins and WCV including construction, operation and maintenance

	Bin			WCV (construction and maintenance)		
	Construction	Maintenance	Unit	18 m^3	6 m^3	Unit
Resource						
Electricity	–	2.90E-4	MJ/kg HDPE	0.04	0.12	MJ/OF tonne
Oil and diesel	0.9073	–	kg/kg HDPE	1.99	1.80	MJ/OF tonne
Lubricating oil	–	–	–	0.03	0.02	kg/OF tonne
Natural gas	0.7306	–	m3/kg HDPE	1.05	0.94	MJ/OF tonne
Coal	0.1039	–	kg/kg HDPE	–	–	–
Energy, hydropower	0.5832	–	MJ/kgHDPE	–	–	–
Energy biomass	0.3127	–	MJ/kg HDPE	–	–	–
Steel	–	–	–	0.15	0.14	kg/OF tonne
Metals	0.0002	–	kg/kg HDPE	0.11	0.10	kg/OF tonne
Other minerals	0.0007	–	kg/kg HDPE	–	–	–
Water	0.0323	6.09E-06	m^3/kg HDPE	2.14E-03	1.93E-03	m^3/OF tonne
(HDPE, Rubber)	–	–	–	0.057	0.051	kg/OF tonne
Emission air						
Particulates	6.4E-04	–	kg/kg HDPE	8.81E-06	7.95E-06	kg/OF tonne
CO fossil	1.2E-02	–	kg/kg HDPE	2.99E-05	2.70E-05	kg/OF tonne
CO_2 fossil	1.6E+ 00	–	kg/kg HDPE	0.019	0.018	kg/OF tonne
CO_2 biogenic	1.1E-02	–	kg/kg HDPE	–	–	–
SO_2	4.1E-03	–	kg/kg HDPE	3.69E-06	3.33E-06	kg/OF tonne
NO_x	3.2E-03	–	kg/kg HDPE	1.85E-04	1.67E-04	kg/OF tonne
Emission water						
COD	1.90E-04	–	kg/kg HDPE	3.88E-06	3.50E-06	kg/OF tonne
BOD5	2.09E-05	–	kg/kg HDPE	3.88E-06	3.50E-06	kg/OF tonne
TOC	1.11E-05	–	kg/kg HDPE	1.70E-06	1.53E-06	kg/OF tonne

emissions generated during AD + composting were by N_2O and VOC. Management of the digestate discharged from the anaerobic digester requires preliminary mechanical separation into a liquid and solid fraction (Rico et al. 2011). 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/OF tonne. The solid fraction was composted to produce a high quality fertilizer. The liquid-solid separation process leads to a reduction from about 20 % to about 95 % of the amount of nutrients in the solid phase, depending on the digestate features and on the technology used in the separation process (Rico et al. 2011). In this study, the amount of nutrients recovered from the production of high quality fertilizer was assumed to be 23 % of that recovered by direct composting of the OF. As known, the biological gasification of the organic matter, and the curing and sieving treatments lead to a significant reduction of the OF mass during composting. This mass reduction can be greatly influenced by local situations, collection methods, and also by the technology used. For this reason, a mass balance was performed on the composting facility operating in the district. For the period from 2006 to 2010, considering 1 tonne of OF at the plant inlet, 600 kg were process losses, 270 kg were process waste, and 130 kg were organic fertilizer. The amount of nutrients in a tonne of organic fertilizer were as follows: $N=14.3$ kg, $K_2O=19.3$ kg, and $P_2O_5=6.74$ kg (Table 5). Dry AD operates at 83 % humidity in the digester. This means that the fresh OF has to be diluted before entering the digester. Usually, a given amount of the liquid fraction of the digestate is used for this purpose. Assuming the same process waste as the composting facility, the AD + compost mass balance was as follows: biogas=0.15 tonne, liquid digestate to WWTP= 0.45m^3, recirculated liquid digestate=1.3 tonne, and fertilizer=0.13 tonne. In accordance with Blengini (2008), the application of compost as organic fertilizer to build up carbon was considered. Reconstitution of the carbon in the soil could prove to be a powerful sink for carbon sequestration. On the basis of the results reported by Linzner and Mostbauer (2005), an average carbon sequestration potential of 173 kg CO_2 equivalent per ton

Table 5 Mass balance and data for LCI of Composting and AD for 1 tonne of OF

Parameter	AD + compost	Unit	Reference
OF inlet	1	tonne	
Compost outlet	0.13	tonne	This study, Bolzonella et al. (2006)
Biogas	0.15	tonne	
To WWTP	0.45	m^3	
To disposal	0.27[a]	tonne	
Energy	11.8[b]; 220[c]	kWh/tonne	Hischier et al. (2010), Di Maria et al. (2013b)
Nutrients and organic C per tonne of organic fertilizer			
N	3.29	kg/tonne	This study, Rico et al. (2011)
K_2O	4.44	kg tonne	
P_2O_5	1.55	kg tonne	
C org.	201	kg tonne	This study
Air emissions per inlet tonne			
N_2O	99.8	g/tonne	Hischier et al. (2010)
NH_3	319	g/tonne	
H_2S	245	g/tonne	
VOC	853	g/tonne	

[a] Landfill

[b] Consumed per tonne of fertilizer produced

[c] Generated per OF tonne

of mature compost was used. LCI of AD was retrieved from ecoinvent v2.2 (Hischier et al. 2010) with respect to dry AD facilities for OF operating in Switzerland from 2000 to 2006. Comparing the OF composition reported in the database with that of Table 1 and considering the technological level of these facilities, the model is consistent with aims of the present study. Adjustment was made for the electrical energy generation (Table 5). Construction and decommissioning, after a working period of 25 years, both of composting and of AD facilities were accounted for (Hischier et al. 2010). Similarly, the WWTP process was retrieved from the ecoinvent v2.2 reporting average data related to Swiss facilities of about 25,000 per capita equivalent. WWTP consisted of three treatment stages as mechanical and physical, biological, and chemical, also including sludge stabilization by anaerobic digestion. The database refers to the year 2000, but considering the level of technology achieved by these facilities and the average technology level of WWTP in the area considered, the model was considered consistent.

2.1.6 Incineration

The LCI of incineration was obtained by modifying the ecoinvent v2.2 database (Hischier et al. 2010), referring to grid incineration facilities operating in Switzerland. The model proposed concerns the combustion of OF. A typical technical configuration of Italian incineration facilities consists of a grid combustor followed by a post combustion chamber and the boiler. After the boiler, the combustion gasses enter the gas cleaning system that consists of dry scrubbing, pre-dusting, the injection of activated carbon for micro-pollutant removal, a chemical reactor for acid gas removal, and fabric filters. Finally, the gas treatment system is equipped with a selective catalytic reactor for further NO_x removal (Turconi et al. 2011). Furthermore, due to climatic conditions and the possible location of the facility, only electrical energy generation was considered. On the basis of average values for similar incinerators currently operating in northern Italy (ISPRA 2013), the average net electrical efficiency, including internal consumptions, was determined (Table 6). Referring to the data reported in Table 1, both the lower heating value (LHV) (kJ/kg) and the amount of ash (kg/OF tonne) were evaluated according to Tillman (1991). Hence, the amount of net electrical energy recoverable was about 300 kWh/OF tonne, whereas fossil fuel consumption was of 14 MJ/OF tonne (Hischier et al. 2010). The chemical composition of the OF was compared with the one considered in the ecoinvent model. Also in this case, the chemical characterization of the OF was very similar to the one in the model, and for this reason, it was considered consistent with the scenario examined. Similarly, using the data in Turconi et al. (2011) and ISPRA (2013), the consistency of the technology with the ecoinvent model was analyzed. The combustion technology along with the boiler were practically equivalent. There were some differences in the gas cleaning system due to the presence of an electrostatic precipitator and a wet scrubber instead of dry scrubbing and pre-dusting. Finally, in both technologies, there was a selective catalytic reduction for NO_x removal. Emissions (Table 6) and reactant consumption were retrieved from Turconi et al.

Table 6 Specific data for the incineration process of the organic fraction

Parameter	Value	Unit	Reference
Solid output (Landfill)	29.5	kg/OF tonne	This study, Tillman (1991)
Energy	310	kWh/OF tonne	This study
Net electrical eff.	22	%	ISPRA (2013)
OF LHV	5,050	kJ/kg	This study, Tillman (1991)
Fossil fuel (natural gas)	14.0	MJ/OF tonne	Hischier et al. (2010)
NO_x	265	g/OF tonne	Turconi et al. (2011)
SO_x	2.7	g/OF tonne	
NH_3	4.8	g/OF tonne	
HCl	12.7	g/OF tonne	
Dioxin	12.1	ngTEQ/OF v	
Other emissions	variable	variable	Hischier et al. (2010)

(2011) for Italian incinerators. Construction and decommissioning after an operating period of 40 years was also considered according to the ecoinvent v2.2 database.

2.1.7 Landfill

Energy recovery from landfill gas (LFG) was assumed only for the scenario with SS=52 % (i.e., AD + composting). Due to the reduction of the biological reactivity by AD + composting, the amount of gas generated and the consequent amount of energy recoverable was assumed, respectively, to be 25 Nm^3/OF tonnen and 33.5 kWh/OF tonne (Di Maria et al. 2013a). This finding was obtained for the typical size of landfills operating in the area considered (i.e., about 1,000,000 m^3) with an effective amount of LFG recoverable for energy generation of 50 %. The amount of LFG collected but not exploitable for energetic use, due to low rate and poor quality, was assumed to be flared (i.e., 6 %). The fraction oxidized by the cover soil was assumed 4 %, whereas 40 % of LFG was emitted in the atmosphere. Both CO_2 generated by the biological process occurring in the landfill and that generated by LFG oxidation were considered biogenic. Other data used for landfill LCI were retrieved from the ELCD 2.0 database (European Commission 2008). This database shows consistency in the amount of LFG generated and effectively exploited for energy recovery (i.e., 50 %), flare utilization, and the amount of methane oxidized by the top cover. The possible role that landfilling can have in contributing to carbon sink reconstitution was neglected. LCI for slag from incineration was assumed in accordance with that proposed by ecoinvent, developed for this purpose. The model concerns the disposal of inorganic waste with organic carbon below 5 % as typical values for incineration slag. Energy and material consumption for landfill construction and management were also accounted for.

2.2 Software used for modeling

The LCA model was implemented using SimaPro8 software (Prè Consultants 2013).

3 Results and discussion

3.1 LCA analysis

In general, with the exception of HTP, the management of a single ton of OF gave lower impact values for the scenario with a SS=0 % (Table 7). This is mainly a consequence of the larger amount of net renewable energy generated by incineration with respect to AD + composting (Tables 5 and 6). Furthermore, both AD + composting generate a non-negligible amount of GHG emissions as N_2O and VOC. Different results were obtained by Khoo et al. (2010) who analyzed several conversion options for food waste in Singapore. Findings show that incineration gave higher GWP and EP values with respect to AD + composting. AP and POCP gave the opposite trend. Similarly in analyzing management systems for biodegradable waste in the municipality of Uppsala (Sweden), Sonesson et al. (2000) found that incineration always gave higher GWP, AP, EP, and POCP values with respect to anaerobic digestion, even if in this case the composting phase was omitted. After analyzing more than 200 LCA studies of waste management, Laurent et al. (2014a, b) observed that there is no definitive agreement on which technology, incineration or AD, performs better for the OF of waste. Figure 2 shows the contribution of the single waste management activities and components falling within the expanded system boundaries to the total values of each impact category (TOTAL). The contribution from bins used during road collection (i.e., SS=0 %) was negligible and for this reason was omitted from the analysis. The other activities

Table 7 Values of the impact categories for managing the organic fraction with SS=0 % and SS=52 %

Impact category	Unit	%SS	
		0	52
Abiotic depletion potential (ADP)	kg Sb eq/tonne	−1.068	−0.431
Global warming potential (100) (GWP_{100})	kg CO_2 eq/tonne	−122.9	180.9
Ozone layer depletion potential (OLDP)	kg CFC-11 eq/tonne	−6.55E-06	−3.08E-06
Human toxicity potential (HTP)	kg 1,4-DB eq tonne	12.73	−12.86
Terrestrial ecotoxicity potential (TEP)	kg 1,4-DB eq/tonne	−0.049	−0.004
Photochemical ozone creation potential (POCP)	kg C_2H_4/tonne	−0.017	0.054
Acidification potential (AP)	kg SO_2 eq/tonne	−0.380	0.170
Eutrophication potential (EP)	kg PO_4 eq/tonne	0.031	0.630

and components considered were *Bags*, *Transport*, *AD + composting*, *Fertilizer*, *Carbon sink (Compost)*, *Avoided energy*, *Incinerator*, *Landfill*. In agreement with Blengini (2008) and Di Maria and Micale (2014), transport contributed only marginally for all the impact categories (Fig. 2a–h) and the two SS intensity scenarios gave quite similar values. The larger amount of avoided energy by OF incineration instead of AD led to larger environmental benefits due to the energetic context considered and to the landfill emissions avoided (Fig. 2). For this reason, in the scenario with SS=0 %, the benefits due to avoided energy compensated largely for the environmental burden generated by the other components and activities for almost all of the impact categories. EP and HTP were exceptions (Fig. 2c, e). In these cases, the environmental burden due to gaseous emissions from the incineration process surpassed the gain due to avoided energy. These results are quite in line with the results reported by Khoo et al. (2010), in particular for EP. For the scenario with SS=52 %, gaseous emissions arising from the AD + composting process were relevant in the determination of AP, GWP, TEP, and POCP (Fig. 2b, d, g, h). In fact, environmental gain due to avoided energy, carbon sink, and avoided fertilizer were lower than the burden generated by process emissions. Bags gave a practically marginal burden for all the impact categories, where values were comparable with the AD + composting and transport emissions. Gas and liquid emissions from landfilling in the scenario with AD + composting were relevant for the determination of EP, GWP, and POCP (Fig. 2c, d, h). Referring to the evaluation of the impacts and resource conservation potential of composting in the Asti district (Italy), Blengini (2008) showed that both process and biogenic emissions from composting significantly affect the GWP, EP, POCP, and AP impact categories. The same author showed that bags used for OF collection had a positive impact but were relevant only in the determination of POCP and OLDP. Avoided mineral fertilizer played a detectable, but marginal role for impact category reduction in the scenario with SS=52 % (Fig. 2a, b, d, h). Carbon sink due to compost use contributed about 20 % to the equivalent CO_2 emission reduction (Fig. 2d). Construction of facilities involved in the two scenarios affected the impact from 1 to 10 % depending on the specific category. All these results show that the critical activities influencing the environmental impact for both scenarios were the amount of renewable energy recoverable and the amount of emissions generated by the processes. In particular, the first aspect is a direct consequence of the Italian energetic mix exploiting a significant fraction of fossil fuels (i.e., about 60 %). For these reasons, a sensitivity analysis was performed adopting a different energetic mix than the Italian one as defined in Table 8 (see Section 3.2).

3.2 Sensitivity analysis

Table 8 reports the percentage of the different energy sources used for generating 1 kWh of electrical energy for Italy (TERNA 2013), Denmark (Energynet 2012), Greece, and Switzerland (Hischier et al. 2010) re-calculated, excluding the percentage of electricity imported. Each mix was chosen for its particular features. The Italian mix consists of about 70 % fossil fuels and about 30 % renewable; Denmark uses about 50 % fossil fuel and 50 % renewable; Greece exploits more than 85 % of fossil fuel, mainly coal, and about 10 %

Fig. 2 Contribution of different activities, components, and processes for ▶ the SS=0 % and SS=52 % scenarios to the life cycle impacts and resource recovery for 1 ton of organic fraction. **a** Abiotic depletion potential (ADP, $kgSb_{eq}$), **b** acidification potential (AP, $kgSO_{4eq}$), **c** eutrophication potential (EP, $kgPO_4^{--}$), **d** global warming potential 100 years (GWP_{100}, $kgCO_{2eq}$), **e** human toxicity potential (HTP, kg1.4-DB_{eq}), **f** ozone layer depletion potential (OLDP, kgCFC-11_{eq}), and **g** terrestrial ecotoxicity potential (TEP, kg 1.4-DB_{eq}), photochemical ozone creation potential (POCP, kgC_2H_{4eq})

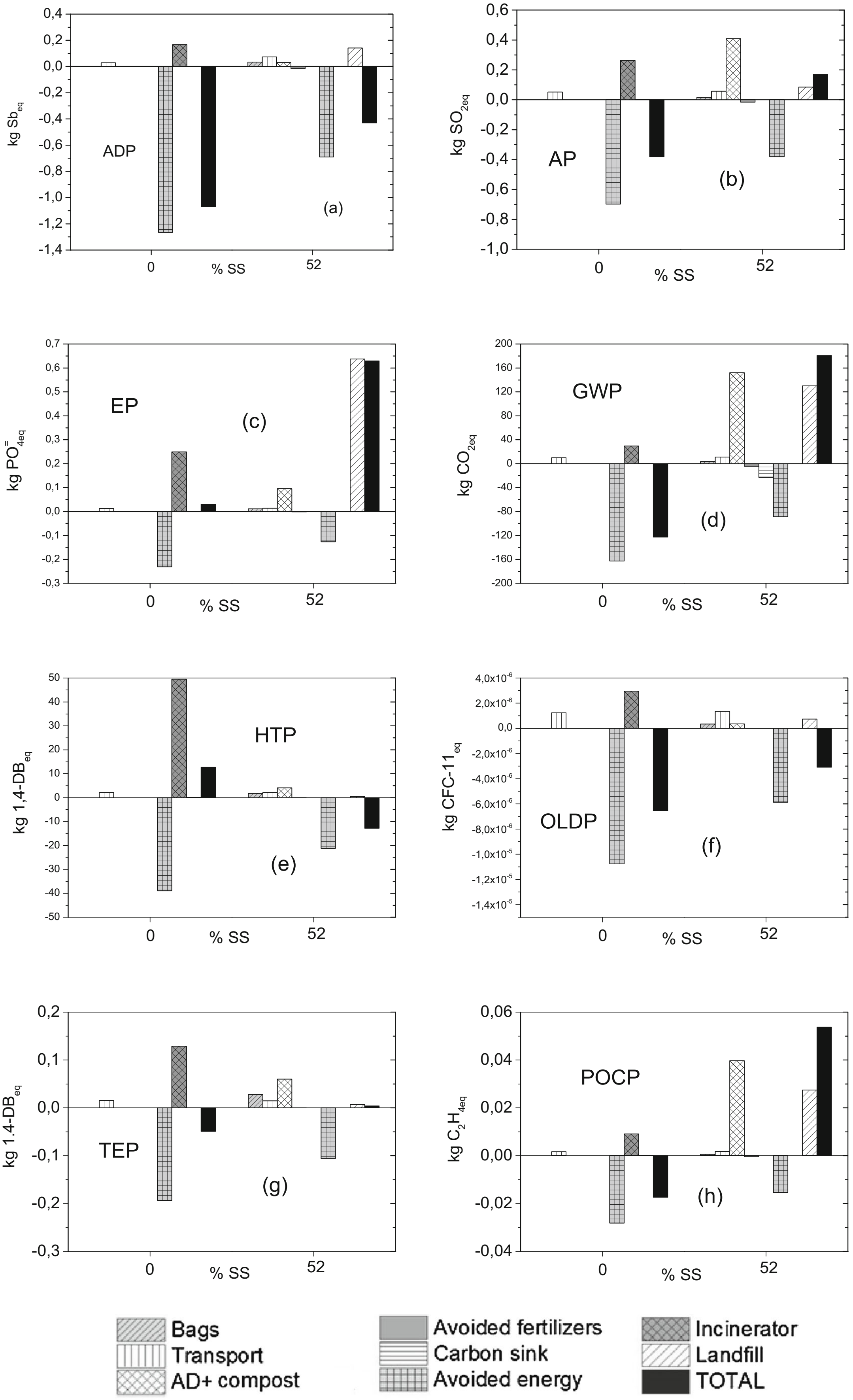
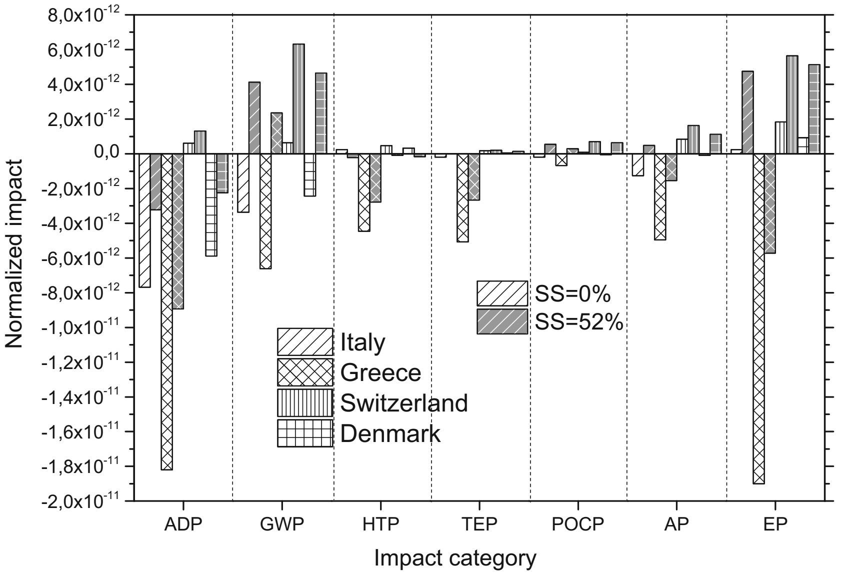

ADP
(a)
kg Sb_{eq}
0,4
0,2
0,0
-0,2
-0,4
-0,6
-0,8
-1,0
-1,2
-1,4
0
% SS
52
AP
(b)
kg SO_{2eq}
0,6
0,4
0,2
0,0
-0,2
-0,4
-0,6
-0,8
-1,0
EP
(c)
kg $PO^{=}_{4eq}$
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
-0,1
-0,2
-0,3
GWP
(d)
kg CO_{2eq}
200
160
120
80
40
0
-40
-80
-120
-160
-200
HTP
(e)
kg 1,4-DB_{eq}
50
40
30
20
10
0
-10
-20
-30
-40
-50
OLDP
(f)
kg CFC-11_{eq}
4,0x10^{-6}
2,0x10^{-6}
0,0
-2,0x10^{-6}
-4,0x10^{-6}
-6,0x10^{-6}
-8,0x10^{-6}
-1,0x10^{-5}
-1,2x10^{-5}
-1,4x10^{-5}
TEP
(g)
kg 1.4-DB_{eq}
0,2
0,1
0,0
-0,1
-0,2
-0,3
POCP
(h)
kg C_2H_{4eq}
0,06
0,04
0,02
0,00
-0,02
-0,04
Bags
Transport
AD+ compost
Avoided fertilizers
Carbon sink
Avoided energy
Incinerator
Landfill
TOTAL

Table 8 Percentage of energy sources exploited for electrical energy generation without imports for Italy, Denmark, Greece, and Switzerland

Energy source	Italy (%)	Denmark	Greece	Switzerland
Non-renewable				
Natural gas and other gases	44.6	14.5	15.1	1.21
Coal and other solids	22.9	35.6	59.3	1.53
Oil	2.26	0.70	14.1	1.07
Nuclear	–	–	–	55.5
Hydropower (pump)	0.64	–	0.90	2.28
Renewable				
Hydropower	13.5	0.05	8.50	36.7
Wind	4.31	35.4	2.01	–
Photovoltaic	6.06	–	–	0.03
Geothermal	1.80	–	–	–
Biogas	1.49	1.27	0.20	0.21
Biomass	1.83	9.56	–	0.18
Waste	0.70	2.74	–	1.31
Reference	TERNA (2013)	Energynet (2012)	Hischier et al. (2010)	Hischier et al. (2010)

renewable; Switzerland generates more than 55 % of electrical energy from nuclear plants and more than 38 % is renewable. On the basis of these data, the consequent normalized (Table 2) impact categories were calculated for both SS intensities (Fig. 3). OLDP assumed values from 100 to 10,000 times lower than those of the other impact categories and for this reason was not included in the figures. There were relevant benefits achievable for the scenario SS=0 % with the Greek mix. In fact, all the impact categories were negative. In the case of the Danish mix, the impact categories gave a trend similar to the Italian one, even if there were lower environmental gains and a higher burden. For the Swiss mix, the emissions related to the avoided energy due to incineration were higher than those generated by the energetic mix for producing the same amount of energy. For the scenario with SS=52 %, there were benefits for the Greek mix, even if lower than those achieved for SS=0 %. This was in accordance with results reported by Antonopoulos et al. (2013). The lower amount of energy avoided per ton of OF and the emissions (i.e., N_2O and VOC) due to the AD + composting process led to positive values of GWP for all the energetic mixes. Generally, the lower was the fraction of renewable energy adopted in the mix considered, the higher were the environmental benefits and *vice versa*. In general, higher environmental benefits of the scenario with SS=0 % with respect to SS=52 % were confirmed for all the energetic mixes analyzed.

Fig. 3 Influence of the different energetic mixes (Table 8) on the impact categories for the scenarios SS=0 % and SS=52 %



4 Conclusions

Overall, the adoption of incineration for managing the organic fraction (OF) of municipal solid waste shows higher environmental gains compared to anaerobic digestion (AD) and composting, mainly due to the higher amount of energy recoverable. This was significantly influenced by the environmental gain due to the avoided emissions for energy production from the energetic mix composed largely of fossil fuels (i.e., Italy). Furthermore, the AD + composting scenario also generated biogenic emissions with a high global warming potential. Among resource conservation potential, avoided fossil fuel was predominant even if avoided mineral fertilizer and carbon sink showed a remarkable role in the reduction of some impact categories. Key findings were as follows: negligible contribution to the total impact of collection, incineration gave environmental gain, and disposal of residues in landfills contributed significantly to the environmental burden of the scenario with AD + composting. If incineration is not viable due to excessive costs, AD + composting is, in any case, recommended providing that residues are managed differently than landfilling.

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