Evaluation of municipal solid waste management scenarios through a LCA approach: a case study

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Abstract

The purpose of this study is to compare the environmental impacts of three different mixed Municipal Solid Waste (MSW) scenarios, by Life Cycle Assessment (LCA) approach.

Starting from the analysis of local mixed MSW management strategies in a territory of central Italy, two additional scenarios were proposed for comparison. The first scenario actually represents the real situation in the study case area and it is mainly based on mechanical pre-treatment of the mixed MSW followed by biological stabilization of wet fraction and incineration of dry fraction in a waste-to-energy plant (S0). Scenarios 1-2 were built around the same entering waste flows of scenario S0, but applying different treatments. Scenario 1 (S1) is based on direct waste-to-energy of total mixed MSW; while in scenario 2 (S2), all the mixed MSW is disposed of in landfill. The Life Cycle Impact Assessment (LCIA) results are here reported only in term of global warming potential (GWP) indicator. Results show that the worst value for GWP indicator is obtained in scenario S2, while the best one is obtained in scenario S1. However, the differences between different the scenarios in terms of global impact are rather low. The direct emissions from waste incineration and landfilling are the main responsible of contribution to the overall indicator value, while the avoided emissions due to energy recovery from waste incineration is the most important negative contribution.

1. INTRODUCTION

Waste can be regarded as a human concept as there appears to be no such thing as waste in nature. The waste products created by a natural process or organism quickly become the raw products used by other processes and organisms. Recycling is predominant, therefore production and decomposition are well balanced and nutrient cycles continuously support the next cycles of production. This is the so-called “circle of life” and it is a strategy clearly related to ensuring stability and sustainability in natural systems. On the other hand there are man-made systems.

Nowadays it is worldwide recognized that the production of waste is counterproductive to the attainment of a sustainable society.

The focus of the study is on municipal solid waste (MSW) management, particularly on the mixed waste generated by households, downstream the separated materials collection. This is due to the fact that mixed MSW is known to be as an important contributor to many different environmental problems, such as global warming.

Life Cycle Assessment (LCA) is a useful tool to evaluate the emissions to the environment caused by MSW management and to assess alternative strategies.

The aim of this study is to carry out the comparison of different mixed MSW management scenarios through a LCA approach and the contribution analysis to identify which are the main processes affecting the LCA results. In the following, the carried out analysis is reported and described according to the LCA phases (ISO 14040-44, 2006): goal and scope definition, inventory analysis, impact assessment and interpretation of results. The inventory analysis used both primary and secondary data, these last were in some cases retrieved from literature sources and in some cases taken from GaBi 6.0 version database.

2. MATERIALS AND METHOD

2.1 LCA – Goal and Scope definition

The goal definition is the first phase of the LCA methodology, in which the purpose of the study is described. It identifies and defines the object of the assessment. The purpose of this LCA study is to compare the environmental impacts in terms of Global Warming Potential (GWP) of three different mixed MSW management scenarios, referring to a case study of a territorial area located in central Italy. Scenario 0 (S0) is the base line scenario and it describes the actual situation in the study case waste management system (WMS), referring to the waste amount produced in 2013: in this case, a small part of mixed MSW is directly disposed to sanitary landfill, a part is directed to the incinerator plant and the main amount is routed to a mechanical and biological treatment (MBT) plant; from the mechanical treatment, according to the separation efficiency, the dry fraction of the mixed waste is routed to the incinerator plant, while the humid fraction is partly disposed to landfill and partly is preventively aerobically stabilized. Scenario 1 (S1) is the "mass burn" scenario, where all the mixed MSW is directly routed to the incinerator plant, while in Scenario 2 (S2) all the mixed MSW is directly disposed to sanitary landfill. This last option is clearly out of the rules stated by the European directives, which require that only pre-treated waste can be landfilled. The described scenarios are shown in Figure 1.
The model boundaries cover bin-to-grave, i.e., from the point where products become waste and put into the waste bin at the waste generation source, to the point where the waste either has been converted into a useful material or into energy in a waste to energy (WtE) plant or has become part of the environment after final disposal. In particular, the analyzed solid waste management system in the study case area includes transportation of waste, mechanical separation and aerobic stabilization, incineration and landfilling of all mixed MSW produced in the area.

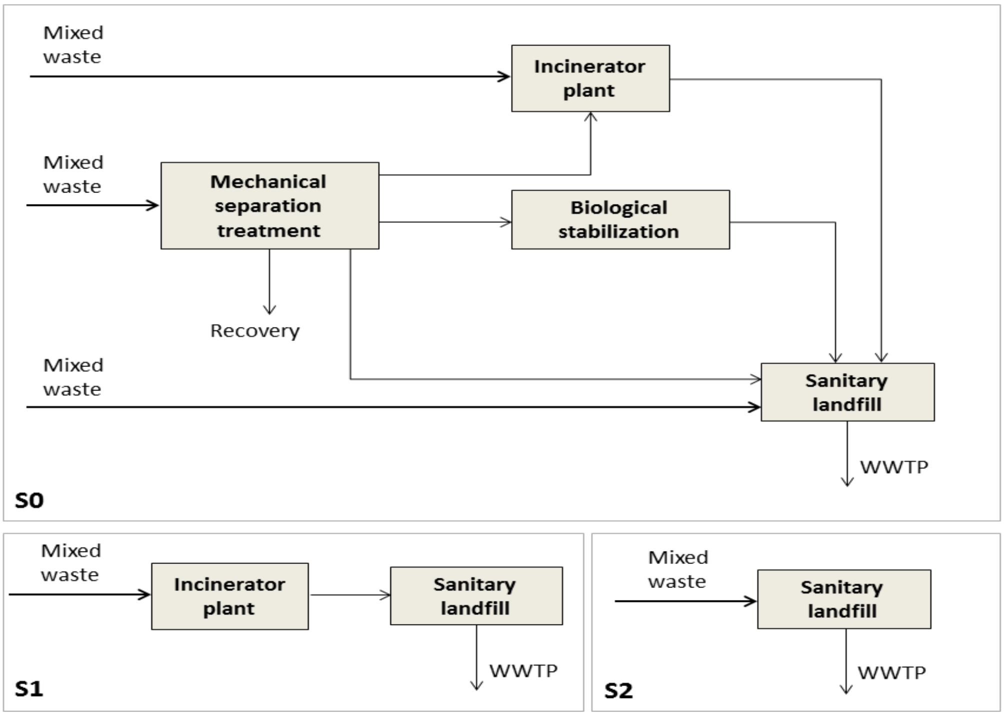


Figure 1 Material flow chart of the three considered MSW management scenarios.

The functional unit (FU) of the LCA is the management of the total amount of mixed MSW during the 2013 in the study case area, which is 94 963 t. The results are reported in reference to 1 t of treated waste.

2.2 LCA – Inventory analysis

In this phase, all the inputs and outputs occurring in the life cycle of the systems previously defined are inventoried to perform a quantitative description of all flows of materials and energy across the system boundary either into or out of the system itself.
The inventory analysis is based on literature data and on GaBi 6.0 database that also includes ecoinvent database. Table 1 summarizes the data sources used in order to analyze the involved processes and technologies.

Table 1 Inventory data source per different processes and technologies

Process/Technology	**Inventory data source**
Mechanical separation	Literature, simple modelling
Biological treatment	Literature, simple modelling
Incineration	Thermodynamic model
Chemicals production	*GaBi* database, literature
Energy production (IT mix)	*GaBi* database
Material recovery	*GaBi* database
Landfilling (including WWTP)	*ecoinvent,* literature

Every waste stream was characterized by a specific material composition, in order to estimate the linked chemical composition, necessary for evaluating the specific inventory of processes as incineration and landfilling. In particular, starting from the specific material composition of the entering MSW (available for the study case area), the material composition after the mechanical separation and the biological treatment was estimated by assuming separation efficiencies and performing a mass balance.

2.2.1 Waste streams

Figure 2 shows the sketch of the waste flows for Scenario 0, which refers to actual situation of the study case area. Links between the different plants are waste flows characterized by the type of waste and its amount.

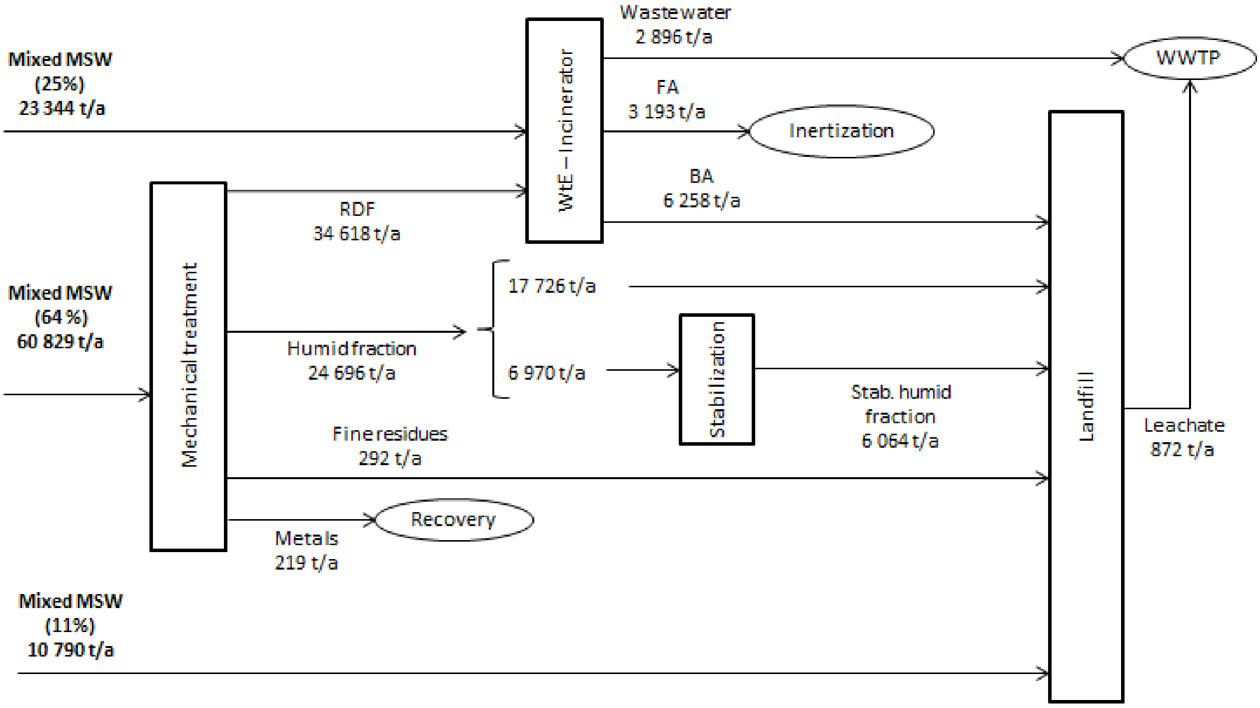


Figure 2 Waste flows for Scenario 0 (S0).

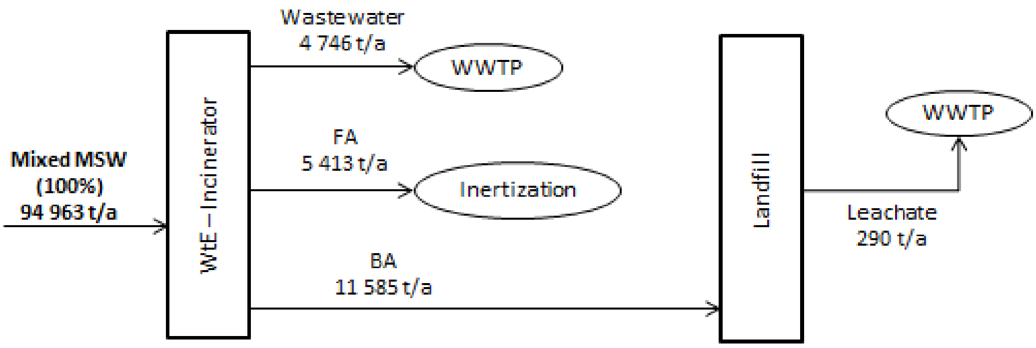


Figure 3 Waste flows for Scenario 1 (S1).

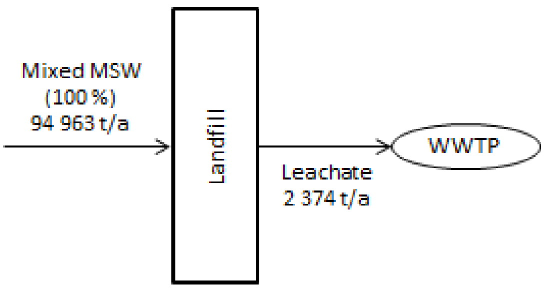


Figure 4 Waste flows for Scenario 2 (S2).

Similarly, figures 3 and 4 show the sketches of waste streams for scenarios 1 and 2, as calculated, according to the assumption made for each scenario.

2.2.2 Inventory data for mechanical and biological plant

The MBT plant is modeled considering its electricity consumptions for the machineries. In particular it was assumed a value of 28 kWh/t_{waste} for the mechanical separation treatment, calculated as a mean value of several literature values (Rezaeyeh et al., 2012; Abeliotis et al.,2011; Bovea et al., 2010; Lombardi et al., 2007; Lombardi et al., 2008). As regards the electricity consumption of the aerobic biological stabilization a value equal to 25 kWh/t_{waste} referring to systems in static piles with forced aeration (APAT, 2002) was assumed. Air emissions from bio-stabilization are neglected because of the use of air cleaning systems (bio-filters). Ferrous metals recovered in the mechanical separation process are accounted for as avoided effects by the production of the same amount of pig iron using raw materials.

2.2.3 Inventory data for WtE - incinerator

The emissions of the waste incineration plant (burning alternatively mixed MSW or dry fraction) and its consumptions/output (chemicals for the flue gas cleaning system, solid output production, and energy recovery) are calculated by a model developed by the Industrial Engineering Department, University of Florence, using EES (Engineering Equation Solver). Table 2 reports output data obtained from EES incinerator model (except from waste water output which is taken from Doka, 2013). Concerning the consumption of cement for fly ash stabilization, a 1:1 ratio was assumed.

Table 2 Inventory data for incinerator plant (EES incinerator model).

	MSW	**Dry fraction**
Air emissions		
CO_2 (fossil) [kg/t_{waste}]	704.8	1065.2
NO_X [kg/t_{waste}]	0.346	0.478
SO_2 [kg/t_{waste}]	0.198	0.216
HCl [g/t_{waste}]	0.257	0.329
HF [g/t_{waste}]	0.0025	0.0012
Electricity production		
Recovery efficiency [%]	19.8	22.3
Self-consumption [%]	12.4	7.7
Net electricity production [kWh/t_{waste}]	743.5	1250.0
Chemicals consumption		
$NaHCO_3$ [kg/t_{waste}]	14.49	18.20
Activated carbon [kg/t_{waste}]	1.47	1.61
NH_3 [kg/t_{waste}]	0.56	0.77
Solid and liquid outputs		
BA [kg/t_{waste}]	122.12	98.55
FA [kg/t_{waste}]	57.04	53.84
Waste water [kg/t_{waste}]	55	45

2.2.4 Inventory data for landfills

The model of waste landfilling consists of two different parts:

- a model for evaluating landfill gas (LFG) generation and emission/exploitation;
- a model for evaluating leachate related emissions.

The first one is based on the calculations and assumptions made by Lombardi et al. (2006); the second one is taken from ecoinvent database and described in Doka (2003). Table 3 reports the annual emission values obtained from ecoinvent landfill model, referring to 1 t of landfilled mixed

MSW. Different values were calculated for the different waste streams disposed in landfill, but they are not reported here for conciseness matter. Table 4 reports other technical parameters and also landfill annual biogas emissions per t of mixed MSW, obtained from LFG generation model. Again, different values were calculated for the other waste streams.

Table 3 Landfill emissions per t of landfilled mixed MSW – evoinvent results.

	MSW
Leachate generation [kg/t_{waste}]	250
Water emissions [g/t_{waste}]	
Ammonium, NH_4^+	744
COD	813
TOC	206
Nitrate, NO_3	2712
Nitrite, NO_2^-	16
Nitrogen, N	20
Phosphate, PO_4^{3-}	6
Air emissions [g/t_{waste}]	
Ammonia, NH_3	1.4
Dinitrogen monoxide, N_2O	3.8
Nitrogen oxides, NO_X	13.8
Hydrogen chloride, HCl	19.5
Hydrogen fluoride, HF	6.4
Phosphorus, P	0.004
Sulphur dioxide, SO_2	25.4

Table 4 Landfill biogas emissions, energy consumptions and energy recovery (mixed MSW case).

		MSW
LFG generation – Lombardi et al. (2006)		
Biogas	[kg/t_{waste}]	186.0
	[Nm^3/t_{waste}]	145.8
Methane, CH_4	[kg/t_{waste}]	51.7
	[Nm3/t_{waste}]	73.9
directly emitted	[kg/t_{waste}]	20.7
captured	[kg/t_{waste}]	31.0
flared	[kg/t_{waste}]	10.8
CHP combustion	[kg/t_{waste}]	20.2
Consumptions - ecoinvent		
Electricity	[kWh/t_{waste}]	8.8
Diesel	[kg/t_{waste}]	1.3
Energy recovery		
CHP electricity efficiency	%	35
CHP thermal efficiency	%	30
Recovered electricity	[kWh/t_{waste}]	98.1
Recovered heat	[MJ/t_{waste}]	302.7

Additional assumptions about landfilling are: the leachate emissions of the first 100 years are collected, discharged to a sewer and treated in a municipal waste water treatment plant. The 100% of digested sludge is incinerated in a sludge incineration plant with a final disposal of solid incineration residues in a sanitary landfill.

2.2.7 Inventory data for transport and electric energy

The system boundaries of this study include also the waste transportation among plants (waste collection is not included). Table 5 describes inventory data for transportation stage. Transports of leachate to waste water treatment plant and transport of sludge were not considered in this study. Regarding the electricity consumption and production the Italian energy mix from *GaBi* was assumed.

Table 5 Inventory data for waste transportation:distances and volume of transportation for different scenarios

From	to	Distance [km]	S0	S1	S2
			Transportation [x 1000 tkm]		
Waste generation	MBT	30	1 820	0	0
	Incinerator	30	700	2 850	0
	Landfill	45	490	0	4 270
MBT	Incinerator	70	2 420	0	0
	Landfill	50	1 190	0	0
Incinerator	Landfill	90	560	1 040	0
	FA stab.	100	320	540	0
			7 510	**4 430**	**4 270**

3. RESULTS AND DISCUSSION

The Life Cycle Impact Assessment (LCIA) phase is aimed at evaluating the significance of potential environmental impacts based on the LCI flow results. The classification procedure involves sorting the inventory results in accordance with the selected impact categories. This sorting takes place in GaBi, where the LCI data is automatically converted to common units and the results are combined. The LCI data is multiplied with the relevant characterization factors in order to obtain LCIA results. CML impact assessment method is applied. As mentioned above, the results for each scenario are here reported only in terms of GWP, expressed in kg CO_2-eq per t of treated mixed MSW.

Figure 5 shows the general results obtained from different scenarios analysis. The results do not include CO_2-biogenic emissions but only CO_2-fossil ones. In fact CO_2-biogenic emissions generated during treatment and disposal of waste, in particular landfilling and incineration, can be considered as neutral contribution.

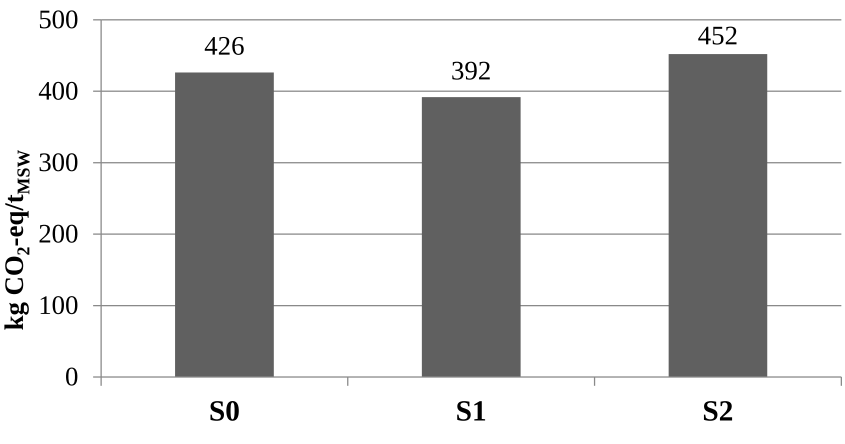
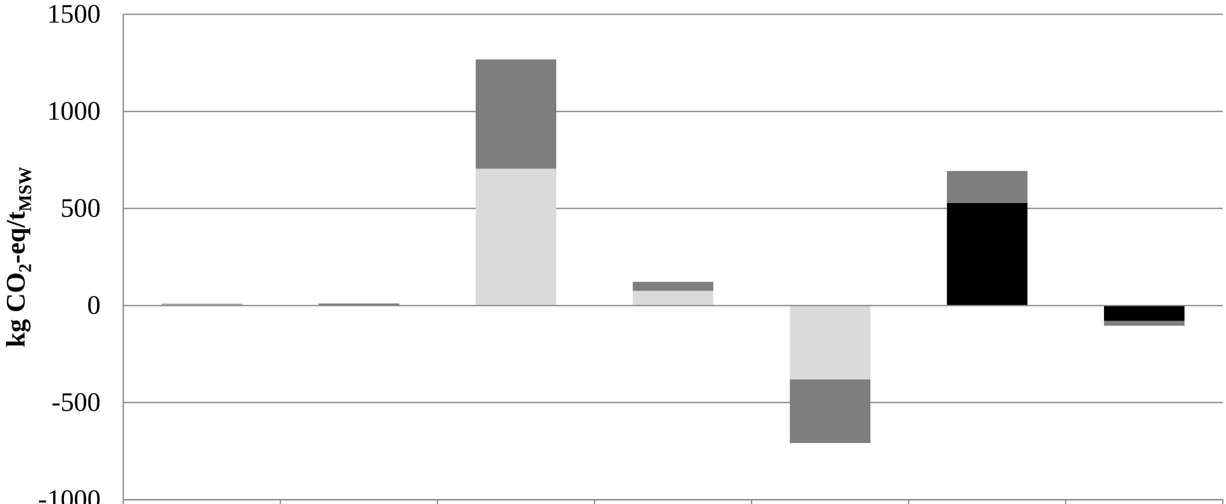


Figure 5 GWP global results for different scenarios.

The best scenario from a GWP point of view is the mass-burn one (S1). However, the differences between scenarios are not as relevant as we could expected. Above all, the comparison between mass-burn and landfilling scenarios (S1 and S2 respectively) should be likely to bring a much greater difference than the one illustrated in figure 5 (e.g. Arena et al., 2003; Eriksson et al., 2005; Miliute & Kazimieras Staniskis, 2010; Manfredi et al., 2011; Sevigné Itoiz et al., 2013; Hupponen et al., 2015). In fact, the direct emissions from mixed MSW incineration are rather high compared to the avoided emissions due to energy recovery, bringing a positive and considerable net contribution to the final GWP balance. This is partly due to the medium/low energy recovery efficiency in the incineration process (i.e. there is no heat recovery) and partly due to the high plastic content of the specific mixed MSW composition (around 22%), that is the main contributor to CO_2 fossil emissions.



	Transp.	MBT_Energy cons.	INC_Direct emissions	INC_APC and WW treat.	INC_Energy recov.	LAND_Direct emissions	LAND_En. recov.
SC0	4,03	10,35	562,71	46,73	-327,52	163,82	-24,47
SC1	2,35	0,00	704,80	75,37	-380,60	0,40	0,00
SC2	2,27	0,00	0,00	0,00	0,00	529,01	-79,23

Figure 6 GWP related produced emissions and avoided emissions from specific processes for different scenarios

To give an idea of how the different sub-processes contribute to the overall of the impacts, the details for GWP indicator are reported in Figure 6. It shows the greenhouse effect for all scenarios, highlighting the contributions by the different sub-processes (transport, MBT, direct emissions from incinerator, emissions from air pollution control chemicals supplying and production, avoided emissions due to energy recovery from waste incineration, direct emissions from landfill and avoided emissions due to energy recovery from LFG combustion). The highest positive impacts are represented by the incineration plants and disposal of waste in landfills, while the highest negative impact is represented by the energy recovery from WtE incineration. Transportation stage and mechanical pre-treatment of the waste have insignificant impacts for each scenario in terms of direct emissions. Even avoided emissions due to energy recovery from LFG exploitation are rather low.

4. CONCLUSIONS

In this study the environmental impacts of three different municipal solid waste management scenarios were evaluated, using the methodology of Life Cycle Assessment. In particular, it was considered the Global Warming impact category, which is related to greenhouse gases emissions. The scenarios differ in the ways the mixed fraction of municipal solid waste are managed: in the base line scenario (S0) a large amount of mixed MSW goes through a mechanical pre-treatment, followed by the biological stabilization of wet fraction and subsequent landfilling of the stabilized material, and the incineration of dry fraction in a waste-to-energy plant; in scenario 1, all the mixed MSW is directly routed to the incinerator plant, while in scenario 2 all the amount of mixed MSW is directly landfilled.

The worst value for GWP impact category is obtained in scenario 2, while the best one is obtained in scenario 1. However, the differences between different scenarios in terms of global impact are rather low.

The direct emissions from waste incineration and landfilling are the main responsible of contributions to the overall indicator value, while the avoided emissions due to energy recovery from waste incineration is the most important negative contribution.

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