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Environmental impact of municipal solid waste management using Life Cycle Assessment: The effect of anaerobic digestion, materials recovery and secondary fuels production

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ABSTRACT

Material and energy recovery from waste is significantly growing its importance in the last decades aiming to reduce the primary resources exploitation and the excessive recourse to incineration and landfilling. Several processes, technologies and methods can be chosen to design a proper waste management system (WMS) so that an objective comparison between alternatives has to be made. To this end, Life Cycle Assessment (LCA) can be used to compare possible alternative scenarios and create an evaluation grid where different environmental parameters are reported. The aim of this work was to compare the environmental impacts of four different scenarios already analysed for technological and economic aspects in a previous work. The scenario taken as base case referred to a real waste management system applied in Caserta Province, an area of 924,614 inhabitants in the Campania region of Southern Italy. The base scenario considers the household separation of waste in five fractions addressed to material recovery (polyethylene, polyethylen-terephtalate, polypropylene, metals, cellulosic fibers, …), composting (biowaste) and incineration (residual waste). The results of the LCA demonstrated that the best scenario is that one including the highest separate collection rate technically and economically feasible to be carried out i.e. 60%, the recourse to anaerobic digestion and biogas production to treat the biowaste separately collected and the maximization of the re-processing of recyclable materials such as PET, HDPE, glass, metals, … In particular, the Global Warming Potential decrease of 166% and the Eutrophication Potential decrease of 646%, when the alternative scenario, including the recalled features is compared to the base-case one. The most important result is that the raised separate collection of recyclable materials utilized as substitutes of raw materials and of biowaste utilized for production of renewable energy helps to mitigate the direct and indirect burdens connected to the overall life cycle of goods production.

1. Introduction

In the last decades, there has been a growing social awareness in respect of environmental issue correlated to the planet "waste" by inducing the proliferation of several proposal to threat the waste in a sustainable way. National and international policy frameworks represented a driven force for this outbreak of technologies and processes [1–3].

The current policy address regarding the solid waste disposal is based on the concept of circular "global" management, a step forward respect to the simply integrated approach. In practice, the

Abbreviations: EFA, energy flow analysis; EP, Eutrophication Potential; GWP, Global Warming Potential; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; LCIA, Life Cycle Impact Assessment; MBT, Mechanical-Biological Treatment; MFA, Material Flow Analysis; MRW, Mixed Recyclable Waste; MRF, Material Recovery Facility; MSW, Municipal Solid Waste; PE, PolyEthilene; PET, PolyEthilenTerephatalate; SFA, Substance Flow Analysis; WMS, Waste Management System; WtE, Waste to Energy.

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waste is seen as a part of the global economic chain and its recovery is convenient, sustainable and essential. The actualization of this vision needs a waste management system (WMS) integrated in the industrial and urban pattern. At the moment the waste management is a standalone system, disconnected by the industrial pattern. The secondary materials are the only points of connection with the industry. A further tentative to connect the WMS to the industrial pattern has been the standardization of the rules to produce the Solid Secondary Fuel (SSF). The utilization of SSF in the traditional cement kiln and steel industries is another point of connection. Anyway, far to be fully integrated, the WMS must be designed to increase the number of connection points with the traditional economy in order to make realistic the circular concept.

Therefore, how a WMS has to be constituted to enforce this connection to industrial fabric? Answer is not unique: depending on waste type, site of production, economy of the region the best WMS can be designed by choosing between alternatives [1–3]. Alternative management system could produce different interactions with the surroundings by means of variables related to environmental, social and economic issues. All these variables depend on the processes included in the system and define the overall waste management sustainability. Environmental, economic and social variables are strongly correlated to the process that leads to the choice of the "best" municipal solid waste management system; the LCA is often used to make the evaluation and comparison between alternatives [2–9]. The integrated design of a WMS must deal with the waste source and with the composition of the collection which is affected by the efficacy of the household waste diversion. By regarding the municipal solid waste, an indiscriminate increase of diversion rate, that is defined as the ratio between the household waste sorted into different fractions (glass, paper&cardboard, mixed recyclable materials, biowaste and the rest) and the total amount of waste, is not necessarily the best choice. In fact, its indiscriminate increasing can lead to worsening of waste quality because of the foreign materials increasing in both biowaste and recyclable waste by creating quality depletion in the recycled goods [10,11].

As already mentioned above, the assessment of the environmental performance of a given solid waste management can be developed by using analytical tools such as material and substance flow analysis (MFA, SFA), energy flow analysis (EFA), risk analysis; in particular, the comparison between different scenarios can be developed by using the LCA tool. This tool uses the output data obtained by MFA, SFA and EFA as input data to the inventory and allows to compare alternative scenarios by means of a series of indexes. The MFA and LCA tools are then integrated and able to give a complete series of results about evolution of the WMS.

In this paper the base case scenario is related to a WMS referred to a wide area included in the Caserta Province having an extension of about 275 km^2, 316.000 inhabitants and a production of municipal solid wastes (MSWs) equal to 148.750 ton per year. The scenario includes the household separation of waste, e kerbside collection, the treatment of each waste flow collected by the householders, recycling and recovery of secondary materials and fuels. The industrial facilities that manage the collected waste are both of private and public ownership; they include a Mechanical-Biological Treatment (MBT), a Waste To Energy plant (WtE), several platforms to pre-treatment of recyclable waste (platform) and several Material Recovery Facilities (MRF) to sort the recyclable waste collected as a mix (Mixed Recyclable Waste - MRW). The alternative scenarios have been designed by following the EU guideline about hierarchy [12,13] and the comparative analysis has been made by using the LCA procedure to evaluate the best scenario regarding the environmental concerns starting by the considerations already reported in the previous work [10]. The objectives of the assessment is to define which of the compared scenarios is the best one, if any, by an environmental point of view. The combination of techno-economical and environmental information drives towards the most sustainable choice in term of waste management planning.

2. Methods and tools

The LCA is a general methodological framework introduced to assess all the environmental impacts related to a product, process or activity by identifying and evaluating the overall resources consumed as well as all the emissions and wastes released into the environment [14,15]. This represent a method that can be used to compare such technologies – scenarios - processes and to evaluate their environmental performances allowing decision makers to be correctly informed [16].

Standard ISO 14040 [17] and 14044 [18] define the four basic steps of the assessment procedure, well described and commented in Refs. [19,20]:

a) Goal and scope definition, which includes the preliminary assumptions about the aim of the study, the functional unit and the boundary of the system.
b) Life cycle inventory (LCI), which consists in the collection and analysis of all material and energy input and output that cross the border between the product or service system and the environment over its whole the life cycle. The input and emission flow are termed *environmental burdens.*
c) Life cycle impact assessment (LCIA), where the environmental impact of the activity is assessed with the use of impact indicators.
d) Life cycle interpretation, which aims to evaluate possible changes or modifications of the system that can reduce its environmental impact.

The LCI is the core of the LCA study and its compilation needs of a lot of reliable data, often taken by on site visit at the real operating facilities of interest. In this paper the LCI is not reported in detail because it can be found in a related previous work [13]. The paper reporting the LCI utilized the MFA as methods to compile the database. This method allowed to obtain all input, output and intermediate flows related to the system under study. In particular, the system has been represented as a flow diagram made by unit processes represented by blocks. Each block was a unit processes. The MFA has been applied to the system and to each unit process as sub-system with a level of detailed analysis more high than usual.

The GABI 7.2.1.12 software, developed by Thinkstep [21] is used for the evaluation of the energetic and environmental impacts of the various processing steps. Two characterization methods have been chosen: Cumulative Energy Demand (CED) provided by Huijbregts M.A.J., Hellweg S., Frischknecht R., Hendriks H.W.M., Hungerbühler K. and Hendriks A.J. [22] and the CML 2 step up by the Centre of Environmental Science of University of Leiden [23]. This is the most comprehensive characterization method specific for Europe which includes quantification of impacts on water, air and land.

The first one has been used to calculate the total energy demand of the activity under study. In fact, the CED method investigates the energy use throughout the life cycle of the analysed system, including direct as well as indirect consumptions of energy due to, e.g., the production of additives or construction materials.

The CML 2 method is applied to evaluate the environmental impacts. In particular, the following environmental impact categories have been selected:

- Global warming potential (GWP), which accounts for the emission of greenhouse gases;
- Human toxicity potential (HTP), which addresses a wide range of toxic substances, including, in this study, the secondary particulate matter;
- Acidification potential (AP), which accounts for the emissions of NO_x, SO_x and ammonia;
- Photochemical ozone creation potential (POCP), which accounts for the substances that cause the photochemical ozone production in the troposphere;
- Abiotic resource depletion (ADP) that represent the natural resources consumption such us metals, crude oil and wind energy [24];
- Eutrophication Potential (EP) that considerate the conversion factor of phosphorous and nitrogen compounds (waste water discharges and air emissions of nitrogen oxides (NO_x) and ammonia (NH_3) into phosphorous equivalents.

Finally, the effects of the variation of the most important input parameters on the results are evaluated and discussed; in particular, the role of very high recovery of organic fractions and the recycling of the recyclable material.

3. Definition of the system under study

3.1. System boundary

The system under study has been depicted in Fig. 1 by highlighting the boundary between the background and the foreground. The foreground system is composed by all the unit processes included in the scenario that must be evaluated and compared with alternatives. The background system is composed by all ancillary and connected processes that provide the foreground system with materials and energy. Environment is the receptor of emissions into air, water and soil. The LCIA quantifies the net impact on it. Fig. 1 graphically describes also the composition of the base-case scenario and individuates the included main unit processes. Each process (unit process), described as a box inside the system, has been quantified in term of mass and energy input and output flows as well as emission. The emission (E in Fig. 1) flows to the environment have been considered in the LCIA. Transport between the unit processes is included in the inventory database.

3.2. Scenario description

The base case scenario is the reference case for which all data are taken by real operating facilities. Alternative scenarios have instead been designed in order to improve the performance parameters [10]. A brief description of the four analysed scenarios is reported in the following. Fig. 2 reports the block diagram of the base scenario together with the main information about treatment capacity; detailed information can be found in Ref. [13] (see Fig. 3):

- **Scenario A: Base-Case (BC50)**: characterized by a source-separated collection having a diversion rate of 50% [10]. The included treatment processes downstream the separate collection are those currently used in the reference area of investigation: i) sorting of recyclable waste (MRW) in MRFs; ii) reprocessing/recycling of materials obtained by the MRFs; iii) pre-treatment of the residual “unsorted” waste in a Mechanical-Biological Treatment (MBT) facility; iv) a waste to energy facility; iv) composting of biowaste separately collected; vi) landfilling of non-recyclables materials and waste from treatment.
The waste flows obtained after kerbside collection are reported in Table 1.
- **Scenario B: Improved Base-Case (BC60)**: it is composed by the same WMS of the BC50 but with the diversion rate increased up to 60%.
- **Scenario C: Alternative Case (AC50):** in the alternative scenarios the system is similar to that described for the base case

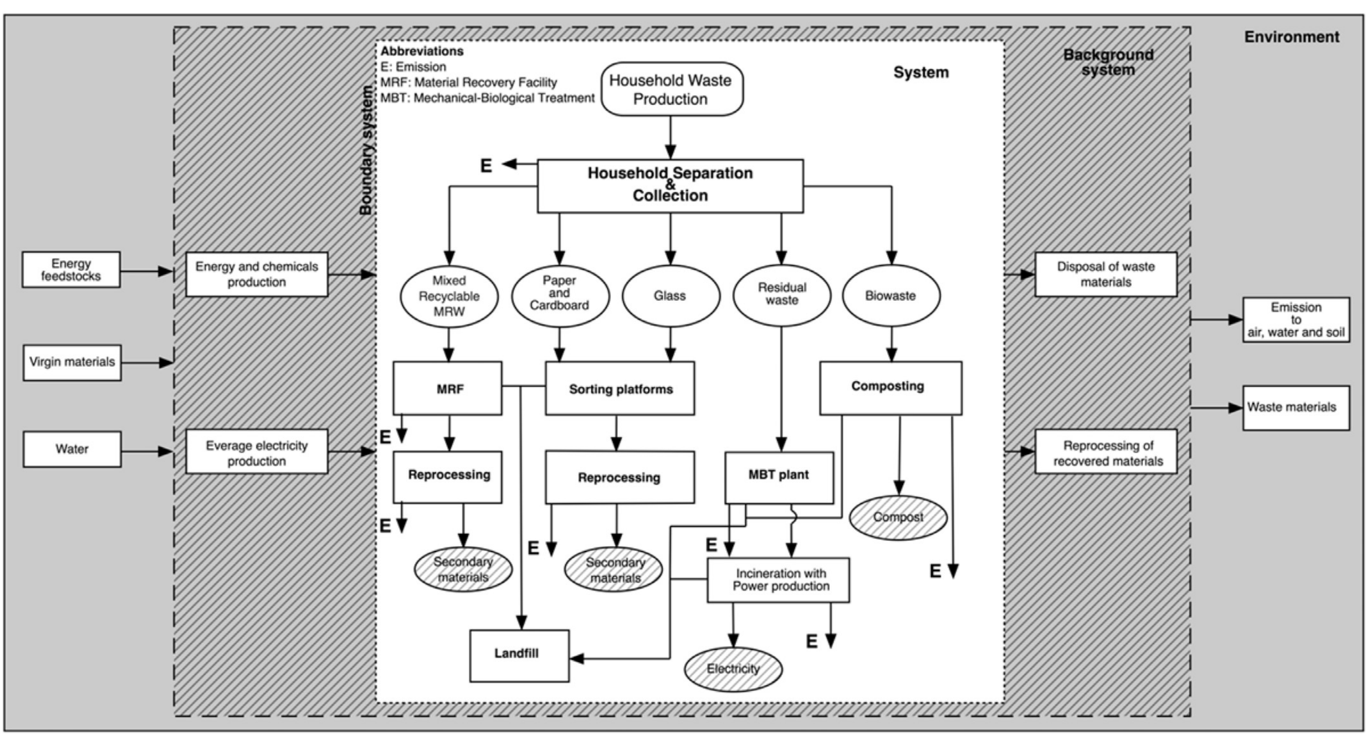

Fig. 1. System boundary of the base case scenario.

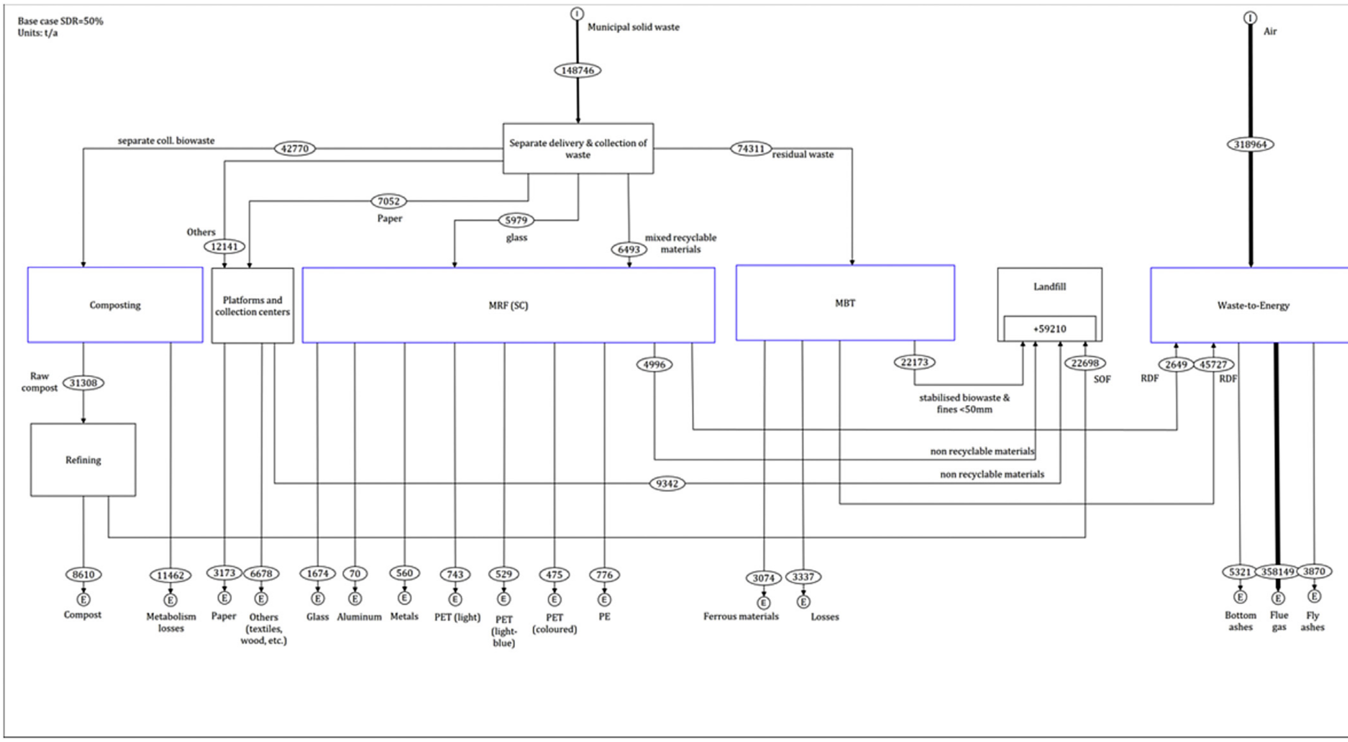

Fig. 2. Base case scenario: the graphical representation of the waste management scenario.

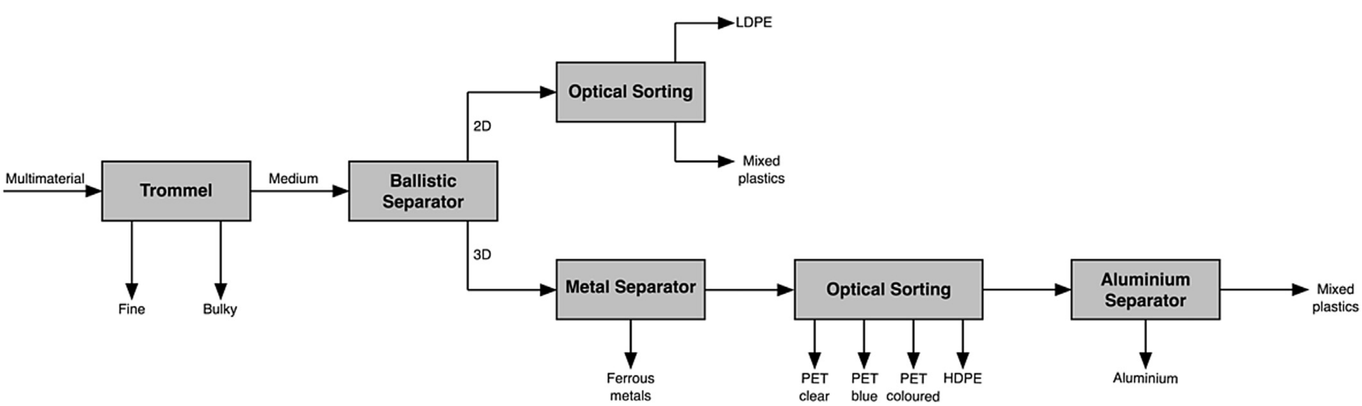

Fig. 3. Flow diagram of the MRF sub-system.

but it is integrated with a material recovery facility (MRF) in the place of MBT with the aim to enhance the material recovery instead of the energy production in the WtE and with an anaerobic digestion process of biowaste in the place of composting. This latter process has been chosen because the biogas and biomethane have an economic value higher than compost; anyway compost of same quality is produced by integrating anaerobic process with an aerobic stage. The waste flows separately collected are reported in Table 1.

- **Scenario D: Improved Alternative Case (AC60):** it is composed by the same WMS of the AC50 but with a diversion rate increased up to 60%.

Table 1
Waste flow rates at different diversion rate (SC50 and SC60).

Fraction	BC50, ton	BC50, %	AC60, ton	AC60, %
Paper and Cardboard	7,052	4.74%	7,170	4.82%
Mixed Recyclable	6,493	4.36%	6,664	4.48%
Glass	5,979	4.02%	6,098	4.10%
Biowaste	42,770	28.75%	50,053	33.6%
Others	12,141	8.16%	19,263	12.9%
Residual Waste	74,311	50.0%	59,498	40.0%
Total Waste	148,746	100%	148,746	100%

3.3. Functional unit

The functional unit of the compared scenarios is 1ton of household waste having the composition, after kerbside collection, coherent to values reported in Table 1.

4. LCI: life cycle inventory

4.1. Unit processes description

A brief description of the unit processes included in all scenarios are reported in the following paragraph, together with the basic data about mass balances and energy consumption.

4.1.1. Platforms

This facility removes impurities by the paper and cardboard addresses to recycling. A typical lay-out includes the following apparatus [25]:

- N°1 Bag opener Coparm Type TR 50 L
- N° 1 Conveyor 7.5 kW
- N° 1 Conveyor 1–5.5 kW
- N° 1 Conveyor 1–9.5 kW
- N° 1 Press Compaction COPARM R120/120 having two engines from 45 kW each
- Plus manual selection of foreign material.

The reported data are related to a plant processing 10.000ton/year.

4.1.2. Material recovery facility

The MRF includes processes the mixed recyclable waste that includes a wide range of different plastics polymers and metals but it does not included glass and paper. This fraction of the collected waste need to undergo an intense sorting in a material recovery facility (MRF) where single polymeric streams, aluminum, ferrous metals and foreign materials are produced [26–28]. The flow diagram is more complex than a simple MBT because the sorting is enhanced to obtain single polymers sub-divided by different colour. A block diagram is reported in Fig. 2. The optical stage is actually formed by several near-infrared apparatuses to perform the accurate sorting. The electrical consumption of this process related to the following equipment and apparatus, assumed to work at 80% of nominal power:

- Total Plant (excluded utilities) 350 kW plus other utilities 60 kW;
- N° 3 Compressor of 75 kW
- N° 1 Compactor of 110 kW;
- N° 1 Compactor of 230 kW;

with total of 975 kW power use.

4.1.3. Anaerobic – aerobic treatment facility

The biowaste collected as separated stream is slightly shredded by means of bag opener and then it undergoes the biologic process. In the case of anaerobic facility, the pre-treated biowaste is digested for 21 days. After this stage of biogas production, the digestate is aerobically composted for 24 days minimum. In the case of composting plant, the anaerobic stage is missing and the overall residence time reaches 90 days.

The facility taken as reference plant is composed by three main zones: pre-treatment, feeding and anaerobic digestion into batch-wise reactors operated under mesophilic conditions 35–40 °C; aerobic stabilization of digestate (solid residue of anaerobic stage) was enhanced by using heated air and refining to obtain compost; the biogas produced by the anaerobic stage (about $12\%_w$ of the biowaste fed into digestors) is sent to Jenbacher engines to produce electricity and thermal energy. The net electricity produced is 204 kWh/ton of biowaste.

4.1.4. Mechanical – biological treatment

The rest-waste separated from MSW is actually sent to MBT plant for the recovery of metals and separation of fine fraction (composed mainly of biodegradable fraction). The facility taken as reference threats more than 200,000ton/year of residual waste from household collection. The sequence of treatment stages in the unit process "MBT" includes: bag opening, storage, sieving in a rotating drum, shredding, bailing, aerobic stabilization (bio-drying) of the fine waste collected by the rotating drum. The waste enters the rotating drum having a 0.05 m mesh to separate biowaste and inert materials addressed to aerobic (biological) stabilization and finally to landfill. The larger material is shredded and addressed to metals removal before to be fed to the incinerator. The residual waste generates about 30% of biowaste + inert material, 5% of metals, 5% of bulky and 60% of refuse derived fuel (mainly plastics and cellulosic-based waste).

4.2. Air emissions

4.2.1. Waste transportation

Emission data from the transportation of waste has been obtained from the GABI database [21] by considering the utilization of a EUR 4 truck having a weight of 20–26 tons and a capacity of 17.3 ton for waste transportation. All paths connecting each municipality to the destination plants (MBT, MRF, platforms, composting and incineration plant) have been calculated by using a suitable web application [29]. Each municipality (indicated by the ID 1, 2, …) has been included in the evaluation in order to obtain the average distance covered (Table 2).

4.2.2. Composting and anaerobic digestion plant

Inventory data about material and energy balance and air emissions have been obtained from a specific on-site campaign at the anaerobic-aerobic integrated facility owned by CEA srl in Caivano [30]. Gaseous emissions are related to two sources: stack from engines and biofilters. These are utilized to threat the air coming from receiving and aerobic stabilization buildings. The abatement of volatile organic compounds in the biofilters was about 90%.

4.2.3. Mechanical-biological plant

Inventory data about material and energy balance and air emissions have been obtained from a specific on-site campaign at the MBT facility owned by GISEC SpA in Santa Maria Capua Vetere. The main source emission is the air dispersed from the biofilters' surface that threat the air flow rate extracted from all the buildings.

4.2.4. Waste-to-Energy plant

Inventory data about material and energy balance and air emissions have been obtained from a specific on-site campaign at the WtE facility owned by A2A SpA in Acerra. The emission of this plant are available on the official website as a result of on-line monitoring.

4.2.5. Material recovery facility

Inventory data about material and energy balance and air emissions have been obtained from a specific on-site campaign at a MRF located in Gricignano di Aversa (Caserta). This MRF manages more than 80,000ton/year of recyclable waste by producing several secondary materials such as PET, HDPE, LDPE, metals. This facility produces diffused emissions in the air due to odour molecules contained in the packaging waste: liquids, detergents, food residues, etc. The evaluation has been made by using data as evaluated in Lotito R., Zaccariello L. and Mastellone M.L. [31].

4.3. Electricity consumption of the unit processes

All data about energy demand for the unit processes included in the selected scenarios are reported in Table 3.

Table 2
Distance between each municipality and the receiving waste treatment plant.

Municipality ID	Biowaste	Glass, MRW, Paper, WEEE, …	Inert Waste, non recyclables, …	Residual Wastes
	Composting, km	MRF, km	Landfill, km	MBT, km
1	80	26	33	30
2	83	10	11	9
3	101	14	4	4
4	96	17	9	5
5	86	17	12	8
6	78	23	30	27
7	96	12	5	2
8	89	11	6	4
9	86	17	24	18
10	85	9	11	9
11	88	9	7	5
12	84	11	9	7
13	74	26	33	30
14	83	14	14	12
15	90	14	12	10
16	99	14	6	3
17	78	23	30	28
Average distance covered	87	16	13	12

Table 3
Energy demand of unit process.

Plant	Energy demand, kWh/t	Energy production, kWh/t
Platform	0.0074	\
MRF/MBT	0.045	\
Composting	39.83	\
WtE	\	0.354
Anaerobic Digestion	\	0.0244

4.4. Avoided burdens for reprocessing processes

Regarding the avoided burdens connected to the substitution of recycled materials to the virgin ones and the energy recovered by the waste, the following assumptions have been made. All materials sorted by sorting platforms and MRFs have been addressed to recycling facility for production of secondary materials and then reprocessed. Cellulosic fibres have been reprocessed in the paper mill to produce low-grades paper (not blenched); ferrous materials has been considered reprocessed in the steel manufacturing plant; glass has been considered to be used in the glasshouse to produce coloured glass; polymers have been addressed to a facility where PET, HDPE, PP are granulated and sold as secondary polymers. The materials recovered by the processes were assumed to substitute the production of raw products with the following substation fractions: paper manufacturing 0.83, polymers reprocessing 0.81, glass making 0.82, metal and aluminium 0.90. The biowaste has been processed to obtain compost and/or biogas, following the different scenarios. The compost has been considered as fertilizer in substitution of peat and spread to land.

The electricity produced by processes displaces the electricity grid mix according to the italian grid data.

The net emission for the material re-processing has been achieved by literature data [32] and reported in Table 4.

5. Interpretation and discussion: environmental impact indicators

Environmental assessment is based on a comparison between the consumptions for recycling/recovery and those required for the production from virgin raw materials. In other words, for each material the emission released during the production from virgin raw material are subtracted from the emission derived from the recycling/recovery processes. The assessment follows a LCA approach, including both direct and indirect emissions separating the emission from material production and energy production. The LCIA results are presented in term of the following indicators: acidification potential, global warming potential, human toxicity, photo-oxidant formation and eutrophication potential.

For each scenario the value of the above-cited indicators was evaluated for all the processes unit included in the system boundary. The environmental indicators have been divided into two sub-categories M and E: M is the total contribution to the given indicators due to the material recovery; E is the total contribution coming from the energy recovery processes. By looking at these sub-categories it is possible to understand which part of the indicators can be addressed to a specific stage. Table 5 reports the values of the indicators disaggregated for the part of the WMS devoted to material recycling (M) and energy recovery (E) as evaluated for each scenario A-B-C-D. The disaggregated values M_A-E_A, M_B-E_B, etc. allows to understand which is the contribution of the process line to the indicator.

Table 4
Avoided emissions of the materials re-processing (expressed per tonne of secondary material produced) [31].

Recycling material	Recycle efficiency	Energy consumption Mj_{eq}	Global warming $KgCO_{2\ eq}$	Acidification $SO_{2,eq}$	Human toxicity 1,4 DCB_{eq}	Photochemical ozone creation $kgC_2H_{4\ eq}$
Paper	83.3%	−14,708	−445	−2.377	−92	−0.172
PET	81.0%	−15,940	−427	−1.397	−179	−0.416
HDPE	81.0%					
PP	81.0%					
Aluminium	100.0%	−174,634	−8,868	−52.803	−40,507	−16.156
Ferrous materials	100.0%	−14,676	−1,292	−4.072	−84	−1,114
Glass	83.5%	−6,415	−643	−3.642	−146	−0.232

The acidification potential for the material recovery chain (M) is characterized by negative values that typifies it as an avoided burden (Fig. 4a). Regarding this indicator, it is evident that the best scenario is the Scenario D for both M and E contributions (see Table 5 and Fig. 4a for details). This is due to the increasing of material recycling by means of the contribution of enhanced separate collection and to the substitution of the MBT with the MRF. In particular the recovery of metals has a strong impact on the decreasing of this indicator as reported in Table 4 (sub-category M). Moreover the production of renewable energy from anaerobic digestion and the associated avoided burdens strongly decrease the sub-category E.

The global warming potential (Fig. 4b) presents a continuous decreasing of the impact moving from A to D scenarios thanks to the decreasing of incineration and landfilling of biogenic waste. In fact, the avoiding of methane emissions produced at landfill sites, where biowaste is disposed of, greatly affect this indicator. The improved environmental performance is also due to the increased material recycling.

The Photo-oxidant formation and the eutrophication potential have the same trend as the GWP and present an improvement by moving from scenario A towards scenario D due to decreasing of flue gas emissions from incineration. The increasing of impact of photo-oxidation between scenario C and D is due to the biogas combustion that increased of 20%.

The human toxicity (Fig. 4e) is negative for all scenarios by confirming that the material and energy recovery decreases the global impact on the environment. Scenario A and B show values of human toxicity of ~ -11.5 Gg 1,4-Dichlorobenzene-eq whereas scenario B and D show human toxicities almost double (~-5 Gg 1,4-Dichlorobenzene-eq.). This result is due to the increased feedstock use (both refuse derived fuel and biogas) in the combined heat and power plants producing energy. The flue gas at the stack and, especially the particulates, strongly affect the human toxicity potential. The CML methodology, which is used in this research, does not directly and separately account for the effect of particulate matter as, for example, done by the ILCD methodology with the Particulate matter/Respiratory inorganics midpoint indicator (kg PM2,.5-Equiv.). However, the particulate matter in the CML methodology is considered by the toxicity indicators which quantify damages to different environments based on both the inherent toxicity of a compound and potential exposure. In any case, all analysed scenarios show a negative human toxicity, underlining the environmental gain associated with the waste management systems analysed.

Our results pointed out that the application of the waste hierarchy as stated by the EU commission in the Directive 2008/98/EC on waste (Waste Framework Directive) does not always represent the best environmental option. In fact, the successive application of the waste hierarchy (prevention, re-use, recycling, energy recovery and disposal) would have shown a higher environmental burden in our case because, following the directive, composting would have been applied to the entire fraction of biodegradable waste. On the contrary, the integrated application of the methods indicated in the waste hierarchy could reduce the impacts of the waste management systems. This has been shown by the integration of the anaerobic digestion for energy recovery first with composting of the digestate for re-use, then. The best solution should be, by following the EU Commission criteria combined with the LCA study, utilise the anaerobic digestion process as the first stage of biowaste treatment so producing biomethane that represents 60% volume of biogas and use this as "upgraded" fuel. The use of methane in substitution of energy mix to produce electric energy produced non excellent results because the avoided burdens can be limited. By way of example, the

Table 5
Disaggregated environmental indicators as evaluated for each scenario.

Scenario	Separate Collection (%)	Acidification Potential (Mg SO2-eq)		Global Warming Potential 100 (Gg CO2-eq)		Human Toxicity (Gg 1,4 Dichlorobenzene-eq)		Photo-oxidant formation (Mg Ethene-eq)		Eutrophication Potential (Mg PO4-eq)	
		M	E	M	E	M	E	M	E	M	E
A	50	−67.8	24.9	−20.6	87.8	−8.5	−3.3	−9.40	19.1	3	51.2
B	60	−61.2	15.0	−15.4	56.3	−8.6	−2.5	−7.80	12.3	6.8	17.6
C	50	−76.4	17.0	−28.4	48.5	−3.3	−2.5	−11.8	0.60	−3.9	4.40
D	60	−103	19.4	−34.2	19.1	−3.8	−0.4	−13.9	4.40	−5	4.60

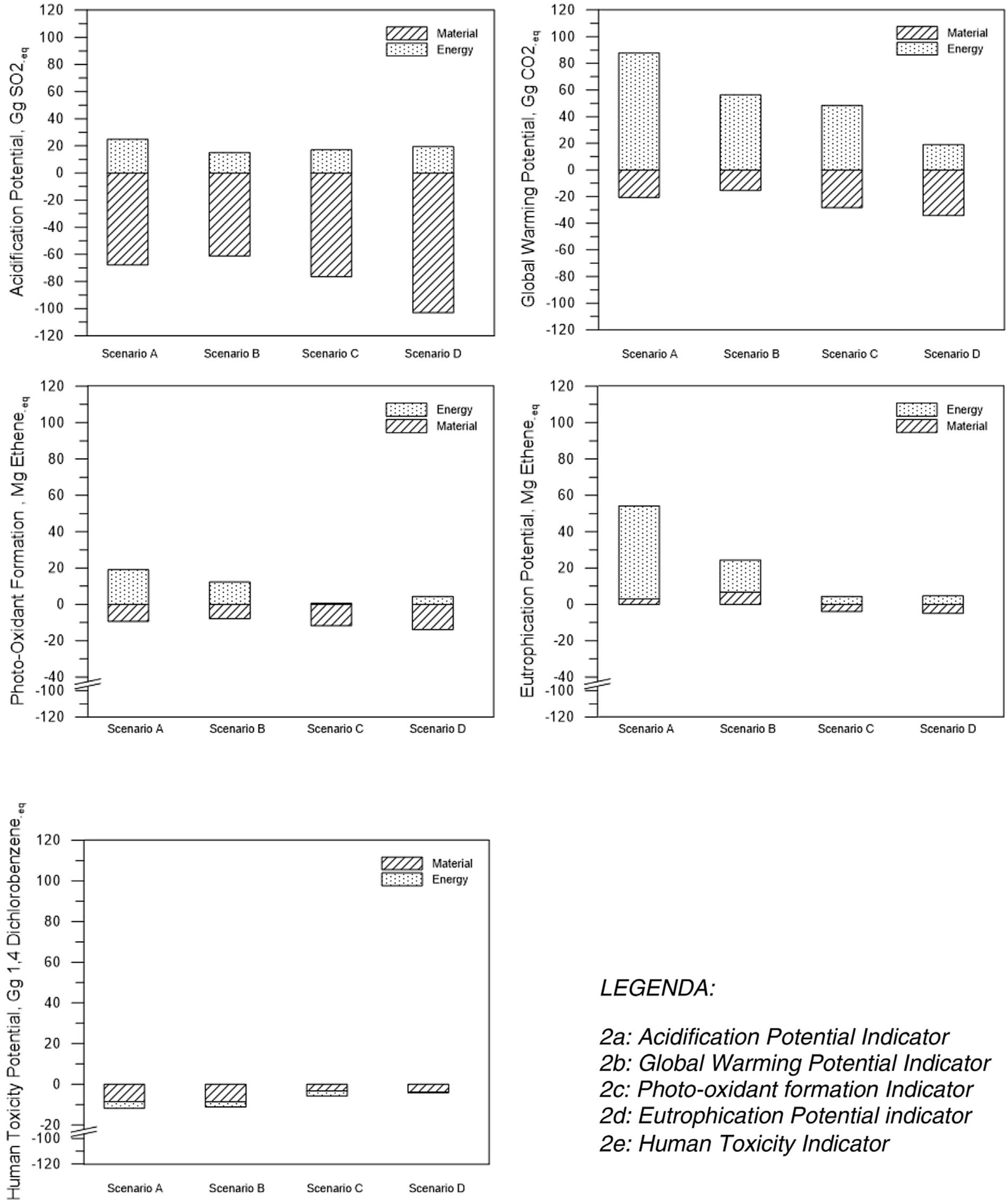

Fig. 4. Group of environmental impact indicators obtained for all scenarios.

energy mix can contain high fractions of renewable energy sources (e.g. hydroelectric, biomass, …) and nuclear energy that is low air emission. The use of biomethane in the place of gasoline and kerosene should lead to very good results, more engaging than those presented. By summarising, the substitution of composting with an aerobic-aerobic combined process is always a good environmental solution and it can be the best one if biomethane is obtained at a grade suitable for kerosene/gasoline substitution.

6. Conclusion

The LCA methodology has been applied to four alternative waste management scenarios differing by the value of diversion rate obtained by means of kerbside collection and for selected waste treatment processes such as anaerobic digestion to produce biogas and electric energy, secondary solid fuel recovery to extend the utilization of this fuel derived from waste even in furnaces different from WtE, material recovery having an established market such as PET, HDPE, paper-based products, glass. The main results are summarised in few points:

- The scenarios designed with higher diversion rates are not necessarily characterized by lower environmental impacts.
- The scenarios including anaerobic digestion integrating the digestate composting showed better performance than those using the pure composting. The anaerobic digestion fulfils two steps of the waste hierarchy at the same time, hence, causing a lower environmental impact than just composting. In fact, through anaerobic digestion the energy is produced by a renewable source so avoiding the production of energy from conventional sources.
- The utilization of material recovery facilities to sort metals and plastics prior the waste-to-energy and prepare a secondary fuel enhances the global environmental impact.

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