Evaluation of potential environmental impacts related to two organic waste treatment options in Italy

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Evaluation of potential environmental impacts related to two organic waste treatment options in Italy

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Abstract

This paper aims at evaluating the environmental impact of two types of organic fraction of municipal solid waste treatment techniques -- composting and anaerobic digestion with post-composting -- by using the life cycle assessment (LCA) methodology. The analysis concerns a facility of municipal solid waste selection and composting, which is located in Italy and where currently there is only a composting line. Two LCA implementations will be presented -- one on the current status and one on the future option – where, according to the plant expansion plan, an anaerobic digestion line is expected to be introduced. This line will allow obtaining electricity and heat as a result of a cogeneration process fuelled by the produced biogas. Following the characterisation results, currently the compost production phase assumes the highest values in 9 out of 18 analysed impact categories, while the landfill phase prevails in the remaining 9. As far as the option to be implemented in the future is concerned, the stage that affects the most (for 8 categories) is sewage treatment, followed by landfill (6 of them) and finally by the compost production (for the remaining 4). The parallel analysis of the two organic waste treatment methods showed that the best one is the anaerobic/composting digestion solution, obtaining lower scores with respect to the sole composting option (apart from the photochemical formation of oxidants impact category).

Abbreviations and Acronyms

AD Anaerobic Digestion

ALO Agricultural Land Occupation

CC Climate Change

CH_4 Methane

CHP Combined Heat and Power

CO_2 Carbon dioxide

FD Fossil Depletion

FE Freshwater Ecotoxicity

FEu Freshwater Eutrophication

FU Functional Unit

HT Human Toxicity

IPCC Intergovernmental Panel on Climate Change

IR Ionising Radiation

LCA Life Cycle Assessment

LCIA Life Cycle Impact Assessment

LCT Life Cycle Thinking

MD Metal Depletion

ME Marine Eutrophication

MEc Marine Ecotoxicity

NLT Natural Land Transformation

OD Ozone Depletion

OFMSW Organic Fraction of Municipal Solid Waste

PMF Particulate Matter Formation

POF Photochemical Oxidant Formation

TA Terrestrial Acidification

TE Terrestrial Ecotoxicity

ULO Urban Land Occupation

WD Water Depletion

1. Introduction

A rise in the amount of the organic waste (wet and green – where the wet fraction is composed predominantly of kitchen waste, whilst the green represents garden scraps), which is collected separately, has been registered in Italy. This was due to the increasing adoption of separate collection and the improvement of the effectiveness of the collection itself, reaching an average growth of almost 10% in the decade 2005-2015 (Centemero *et al*., 2017). Fourteen million tonnes of municipal waste were source separated in the country in 2015 (corresponding to 47.5% of the total municipal waste produced). The sorted organic fraction (wet and green waste) was 6,072,000 tonnes[1] in 2015 (Centemero *et al*., 2017), exceeding the threshold of 100 kg per capita per year (national average value), thus recording an increase of 6.1% in collected organic waste between 2014 and 2015 (Centemero *et al*., 2017).

The biological treatment of municipal waste in Italy takes place through the following types of plants:

- Composting plants (aerobic digestion);
- Anaerobic digestion plants (AD);
- Integrated aerobic/anaerobic treatment plants.

The total number of plants operating in 2015 in Italy was 263 for composting, 26 for AD/composting and 20 for AD only. The majority of these is concentrated in the northern region. Furthermore, in some regions of the Central and Southern Italy, the facilities are not sufficient enough to guarantee a full treatment of the collected fractions; therefore, there are also some extra-regional transports, especially for the wet fraction (Centemero *et al*., 2017).
The management of organic waste deriving from separate collection is mainly performed via composting. In particular, 81.8% of the source separated organic municipal waste is subject to this technique. However, even if the overall treatment capacity remained virtually unchanged compared to 2014, there has been a conversion of conventional composting plants into integrated AD/composting plants (+161.000 tonnes) (Centemero *et al.*, 2017). As a simple definition, composting refers to a biodegradations process of a mixture of substrates carried out by a microbial community composed of various populations in aerobic conditions and in the solid states (Insam and de Bertoldi, 2011), while AD is a process in which

[1] Based on the historical data for separate collection of the individual fractions of wet and green waste -- available in the ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale - Italian Institute for Environmental Protection and Research) Urban Waste Reports until the 2013 edition -- the Italian Consortium of Composters estimated that in 2015 nearly 4 million tonnes of wet waste (approx. 66 kg per capita per year) and 2.07 million tonnes of green waste (approx. 34 kg per capita per year) were collected.

organic materials are subject to a microbial decomposition in an oxygen-free environment (Rajaeifar *et al.*, 2017). These systems, indeed, combine material recovery with energy recovery, obtaining two types of outputs: a semi-solid residue, also known as digestate (Rajaeifar *et al.*, 2017), and biogas, principally comprising CH_4 and CO_2. The former is generally used in gardening or agriculture as a soil improver, whilst the latter for the replacement of non-renewable energy sources. Indeed, according to Pande and Bhaskarwar (2012), biogas from waste and residues is included in the second-generation biofuel category (Rathore *et al.*, 2016).

Therefore, this AD-related activity can be included in the biorefinery one. Indeed, the International Energy Agency (IEA) in Bioenergy Task 42 defines biorefining as "the sustainable processing of biomass into a spectrum of marketable food and feed ingredients, bio-based products (chemicals, materials) and bioenergy (biofuels, power and/or heat)" (IEA, 2014). The "brown biorefinery", in particular, refers to those categories of biorefinery that are based on the availability of sludge and household waste [Lange, 2017, in (Manan and Webb, 2017)]. The biorefinery concept that has been growing in prominence and importance, driven by industry needs for business development and resource efficiency as well as policies that promote the sustainable use of biomass (Hagman *et al.*, 2018). Biorefineries can provide a significant contribution to sustainable development by generating added value to the sustainable biomass use and by producing a range of bio-based products (food, feed, materials, chemicals) and bioenergy (fuels, power, and/or heat) simultaneously [de Jong and Jungmeier, 2015, (in Manan and Webb, 2017)]. Finally, the implementation of systems that strengthen the connection between waste management and the transformation of raw materials (Circular Integrated Waste Management Systems (CIWMSs)) should be promoted [Cobo *et al.*, 2017, in (Cobo *et al.*, 2018)].

AD is one of the most widely investigated methods used in the production of energy from different kinds of organic waste (Rafieenia *et al.*, 2017). In order for the choices of decision makers to be facilitated with regard to their objectives and performance, several types of methods can be used, i.e., for the analysis of the environmental, economic and social aspects of a waste treatment process. When it comes to the environmental aspect, a substantial amount of research efforts has been devoted to the use of exergy-based approaches for the analysis and the optimisation of various waste-to-energy plants (Barati *et al.*, 2017). There are different analyses that investigate the exergetic performance of organic fraction of municipal solid waste (OFMSW) treatments, such as in Barati *et al.* (2017), where a comprehensive exergy analysis of a gas engine-equipped AD plant producing electricity and biofertilisers from the OFMSW to valuate thermodynamically-efficient and environmentally-benign waste-to-energy plants is applied. Furthermore, Aghbashlo *et al.* (2018a) conducted a detailed exergy analysis of a lignocellulosic biorefinery annexed to a sugar mill.

Nevertheless, an exergy analysis can only identify, locate and quantify the thermodynamic inefficiencies (Aghbashlo *et al.*, 2018a). The design of cost-effective and environmentally-friendly engineering processes can be achieved by elaborated extensions of the exergy analysis, i.e., exergoeconomic and exergoenvironmental approaches, respectively (Aghbashlo and Rosen, 2018). These analyses could provide more informative results and yield additional insights that cannot be inferred from the conventional exergy analysis and economic/environmental accounting methods (Aghbashlo *et al.*, 2018b). There is a great number of approaches that have been introduced by integrating the exergy concept with economic and environmental constraints; however, the exergoeconomic and exergoenvironmental analyses have gained popularity for component-level analyses of energy systems (Rosen, 2018). Nonetheless, this type of method excludes the social issues. Technical feasibility, socio-economic benefits, and environmental impacts are addressed to provide decisions that may lead to the appropriate waste management process (Almeida *et al.*, 2017).

There are some studies that present a complete vision of the sustainable municipal waste management; some of these, indeed, show an evaluation that follows the three pillars of sustainability aspects (environmental, social and economic), such as Menikpura *et al.*, 2013; Tulokhonova and Ulanova, 2013; Pour *et al.*, 2017; Aleisa and Al-Jarallah, 2018; Iacovidou and Voulvoulis, 2018. It often emerged that the best choice is not the same for all three pillars of sustainability (Klang *et al.*, 2008). Kijak and Moy (2004) proposed a decision support framework to achieve sustainable waste management practices by balancing environmental, social and economic dimensions at global, regional and community levels appropriately. For this process, LCA is used as the base. Zhou *et al.* (2018) proposed a comprehensive review of evaluation tools based on the life cycle thinking (LCT) concept, as applied to waste-to-energy (WtE). However, with regard to the social issues, a review on conventional waste treatment was mandatory because only a few social life cycle assessment and other types of extended method of evaluations are still less compared with LCA (Zhou *et al.*, 2018). Allesch and Brunner (2014) reviewed 151 studies on solid waste management. The results show that approximately 40% of the reviewed articles are life cycle assessment-based and more than 50% apply scenario analysis in order to identify the best waste management options. Circa 90% of the reviewed studies considered environmental impacts, 45% of them considered the economic impacts, and only 19% of the reviewed studies considered social issues. However, only 28 of the 151 studies analysed the impacts on all three pillars of sustainability.

Moreover, given the fact that there was no up-to-date systematic literature review on this topic within the scientific literature, one was performed by the authors (Mancini *et al*., 2017a) by following a standardised checklist (Zumsteg *et al*., 2012). The review aimed at investigating the generally preferable option (from an environmental point of view) for the treatment of the OFMSW (simple composting or AD combined with composting). This showed that despite substantial differences between the studies, it is energy recovery of OFMSW that is considered to be preferable to the material one, through the integration of AD/composting, simple anaerobic digestion and in some cases, waste-to-energy. Nevertheless, it should be kept in mind that in some geographical and social contexts, although AD may record better performance, it still remains an expensive and complex (from a technological point of view) option, thus forcing city managers to adopt less efficient but certainly simpler solutions, such as material recovery (Komakech *et al*., 2015). An example is registered in South Africa, which fights against a strong energy crisis, and where AD had better performance in categories, such as global warming potential, eutrophication and energy demand (Komakech *et al*., 2015). However, it was considered technologically more complex to manage and more financial investments are needed with respect to other analysed biodegradable waste treatment technologies. Such an emblematic case could suggest general considerations regarding the need to adopt the LCT approach on each front in order to obtain complete information of the analysed options (from an economic and social points of view, as well) and make even more conscious choices. Finally, another finding of the review suggested the use of a specific mass of organic waste as the functional unit (FU) in most of the examined LCA studies.

In general, the reviewed literature showed with regard to composting and AD that the most frequently analysed impact categories within the various studies included climate change, acidification and eutrophication. It demonstrated that the AD processes followed by composting obtain better results from an environmental point of view. For instance, in Khoo *et al*. (2010) global warming, eutrophication, and acidification are higher in composting, whilst photochemical oxidation appears to be the sole impact category to have a higher score in anaerobic digestion with post composting. Moreover, Thyberg and Tonjes (2017) state that the AD/composting scenario delivers better results for all analysed categories, apart from marine eutrophication. When it comes to eutrophication, ADEME (2007) also believes that composting is preferable. Bernstad and la Cour Jansen (2011) conclude their study by stating that the composting process can bring environmental benefits only if specific conditions are met: approximately 100% of the N-losses during composting have to be emitted as N_2 and the digestate obtained by AD to be used on clay soils that are of high nitrates leaching risks. They also state that for the global warming potential, composting can be better only if the best bio-filter technologies for emissions sequestration are used. The ozone depletion potential-related impacts are not significant for all compared scenarios (Bernstad and la Cour Jansen, 2011).

Di Ciaula *et al*. (2015) believe that composting is the only one to guarantee the most appropriate material recovery and the highest contribution of organic carbon to the soil, as it works as a carbon sink, which is an aspect that was taken into consideration in article 5 of the Paris Agreement (United Nations, 2015).

More into detail, ammonia appears to be one of the most responsible emissions from compost for several impact categories, such as acidification, photochemical oxidant formation, eutrophication (Bernstad and la Cour Jansen, 2011), whilst ammonia along with NO_x emissions on eutrophication (Khoo *et al*., 2010) and ammonia with $PM_{2.5}$ for particulate matter (when digestate is used in agriculture) (Cristóbal *et al*., 2016). On the other hand, NO_3^- emissions in ground and underground water influence marine eutrophication (Cristóbal *et al*., 2016). Regarding the energy consumption, it was found that this is very important for climate change. When it comes to the composting and AD option, the substitution of electricity deriving from fossil fuels with biogas entails a reduction in this category (Takata *et al*., 2013; Cristóbal *et al*., 2016) along with ozone depletion (Cristóbal *et al*., 2016). For this reason, the inclusion of AD helps to reduce climate change-related emissions (Khoo *et al*., 2010; Dong *et al*., 2013; Takata *et al*., 2013; Cristóbal *et al*., 2016; Thyberg and Tonjes, 2017). Khoo *et al*. (2010) believe that such a reduction (due to AD with post composting) is possible through the biogas energy recovery and the CO_2 sequestration with the compost. With regard to the climate change-related emissions, Takata *et al.* (2013) state that it is energy consumption to blame for composting processes and the wastewater treatment for AD.

The aim of the authors was to highlight the environmental aspects on overall composting plant; for this reason, an LCA approach was chosen including an LCT concept in the study. In this context, the objective of this paper was to include the LCT concept via the LCA methodology for a composting plant, located in the Abruzzo region, in Southern Italy, for the regional context of which, no similar case studies were found. More specifically, the objective was to identify the environmental hotspots of two OFMSW treatment options for this composting plant. Currently, the plant uses a traditional composting technique. However, the managers plan to expand its facilities, thus obtaining an AD line (along with the already existing line) in order to obtain biogas, which would be used to produce electricity and heat (for use entirely within the facility). This article is structured as follows: first, the specific case study is described in Section 2, where the

two options and the adopted methodology are presented. In Section 3, the obtained results are presented and discussed. Furthermore, in the life cycle impact assessment (LCIA) phase, an analysis of the significance of the various life cycle phases and processes for the various environmental categories is presented, as well. Finally, the conclusions of the article are drawn in Section 4.

2. The case study

The case study of this article consists in the use of the LCA methodology to assess in parallel two treatment processes of the OFMSW: i) composting and ii) AD followed by composting. The analysis carried out concerns a facility for municipal solid waste (from source segregated collection system) selection and composting, which is located in the province of L'Aquila, Italy; that facility currently features only a composting line; however, based on an expansion plan for that plant, an AD line is expected to be introduced (Mancini *et al.*, 2017b). This line will allow the facility to obtain electricity and heat by means of a CHP process fuelled by the produced biogas. The LCA methodology was implemented for two scenarios of waste treatment options: one based on the current option ("A") and one on the future option ("B").

2.1. Processes description

Currently, the plant is equipped with an aerobic treatment line for organic waste. The amount of waste treated in 2015 was 27,878.28 tonnes. The organic fraction components (per European Waste Catalogue –EWC– code) are listed in Tab. 1.

Tab. 1 Organic material input types per EWC code (EPA, 2002), taken from the company under study.

EWC CODES	*DESCRIPTION*
20 01 08	*biodegradable kitchen and canteen waste*
20 01 38	*wood other than that mentioned in 20 01 37*
20 02 01	*biodegradable waste*
02 01 07	*waste from forestry*

The present composting process (“A” option, Fig. 1) begins with the organic waste reception in a storage area, where the green one undergoes a mechanical pre-treatment (via a chipper) to be subsequently sent, along with the organic and the recycling fractions (in the right proportions) –see Fig.1–, into an electric screw mixer that crushes the bags containing OFMSW and homogenises the organic material. Once ready, the mixture is transported via wheeled loaders to bio-cells, where the accelerated bio-oxidation phase will be activated for about 15 days. The temperature reaches and settles at 55°C for at least three days. Then it cools down to 40°C (but not lower than that). As soon as this is completed, the biomass is loaded again on wheeled loaders and transferred to the aging yard, where it remains for about three weeks. As the process is static, the pavement of the bio-cells and of the aging yard are perforated to favour the aerobic conditions and, at the same time, the draining of the leachate. Within the same maturation area, the product subsequently undergoes a sorting process through a sieving machine, which delivers three outputs: the compost (size: 0-15 mm), used as an organic fertiliser for agricultural applications, in particular, it is used by the farmers in the Fucino Valley, which is located a few kilometres away from the facilities (please refer to Figs. 1 and 2); a lignocellulosic intermediate sublayer fraction (size: 15-60 mm) to be recirculated internally in the mixture; a predominantly plastic scrap fraction (size: over 60 mm) to be disposed of in landfill. The landfill lies about 140 km away from the facilities. The entire processing cycle is carried out in a closed environment, equipped with an exhaust system and exhaust air treatment. The latter consists of two scrubbers and a bio-filter, which is composed of a tub of lignocellulose filtering material, such as cortices and roots. Moreover, the leachate is drained through a grid system, delivered to a collection tank and finally sent to a sewage treatment plant. Overall, the composting process takes approximately 40 days. With regard to transports, the vehicles used for compost distribution can carry a maximum load of 10 to 11 tonnes, while those used for landfill have a maximum capacity of 25 tonnes. The sewage treatment plant is located about 103 km away from the facilities and transport is performed by 16/32-tonnes trucks. All outbound trips are carried out at full load, whilst they return empty. The "B" option (Fig. 2) was modelled based on the expansion plan that would be implemented over the next few years. This presumes an AD line supporting the current composting line that would address some of the incoming organic waste. In this second option, after the storage, a pre-treatment phase of OFMSW is expected through disk scrubbing, from which two fractions would be obtained: the heavy and light fractions, which would be sent for composting and AD, respectively. The AD line would allow the treatment of 34% of the organic material entering the plant. This is a dry thermophilic digestion process. The biogas and the digestate would then be the outputs of the process. It is expected to produce 3,000 tonnes/year of biogas

through a co-generation engine of 800 kW_e and 500 kW_t. These would be used to meet partially the energy requirements of the plant. The energy required to meet the remaining needs would be provided by the grid (Italian electric mix), which currently supplies energy for the facilities ("A" option). The digestate will undergo further stabilisation by passing to the composting line, thus becoming an input of the mixing process together with the heavy fraction, the recirculation fraction and the green waste. The phases of the composting process will remain essentially unchanged as in the current situation. Some differences are found only in the maturation process, which in case of "A" is single-step, while in "B" it would be two-step in order to ensure a greater stabilisation of the final product and would occur through a further maturation period of the compostable mixture. The same goes for the screening process, which would be divided into two stages in "B" (whilst in "A" it takes place in a single stage). In the first stage, the following fractions would be obtained:

1) compost (size: 10-15 mm) ready for sale. The compost will be used entirely for agriculture, as in option “A”;
2) a heavy fraction, which is sent to the second stage.

The second stage consists in passing the material to a stellar screening with a spacing of 65-80 mm, from which the following fractions would be obtained:

1) a lignocellulosic fraction (to be recycled);
2) a scrap fraction (size> 65-80 mm) which would be sent to landfill.

This second option “B” was designed to handle an annual flow of incoming organic waste of 58,500 tonnes/year.

In order for biogas losses to be prevented, system monitoring can be crucial (Bolin *et al.*, 2009, [Berglund and Böjresson (2003) in Bernstad and la Cour Jansen, 2011]). Indeed, the biogas losses in the atmosphere may influence greatly the global warming category (Bolin *et al.*, 2009). The plant to be implemented will include a biogas combustion system via a safety flare, located on the digester. As a result of flaring, the methane contained in biogas would produce biogenic CO_2, which is considered to be neutral in terms of potentially contributing to global warming (Arzoumanidis *et al.*, 2014). Therefore, from a methodological viewpoint and given the safety systems to be implemented, for this study these losses were assumed to be close to zero, in accordance with the IPCC guidelines (2006).

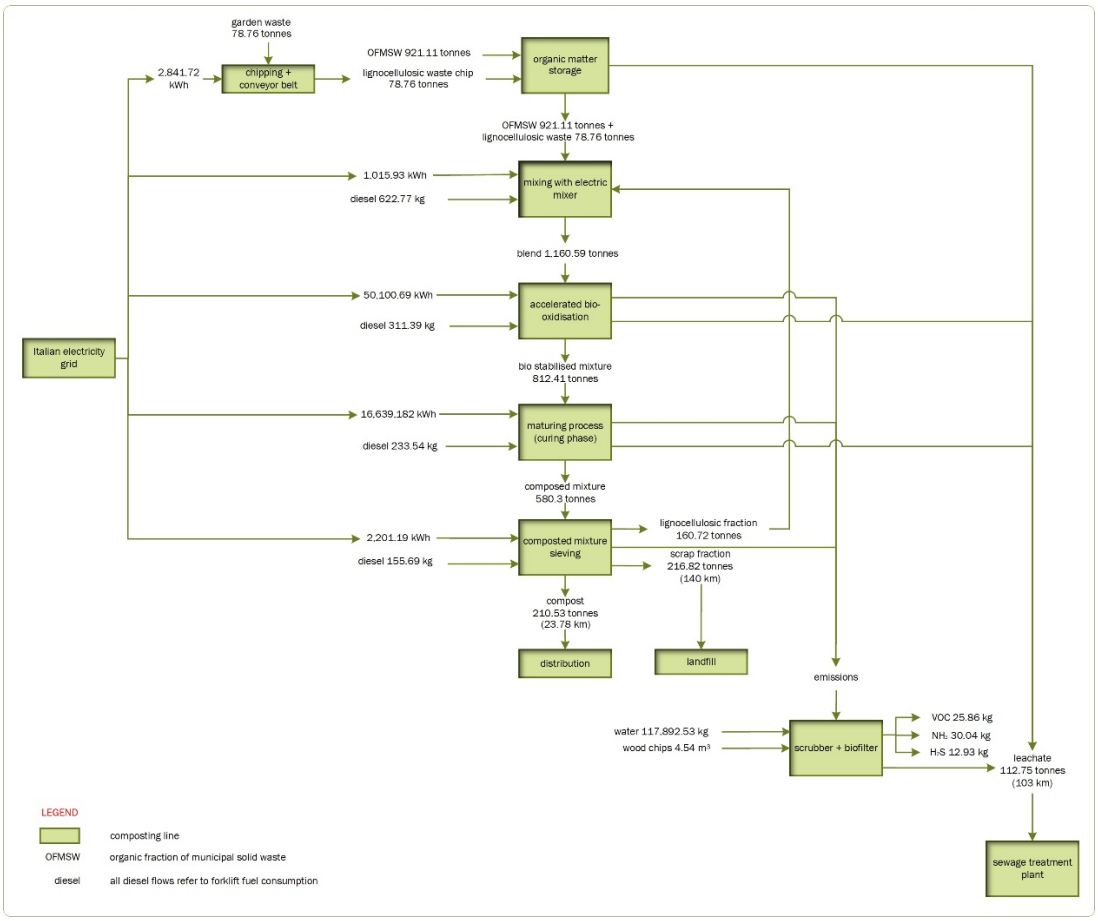

Fig. 1 System boundaries simplified scheme of option "A"- Composting (only the emissions calculated by the Authors are shown; elaborated by the Authors).

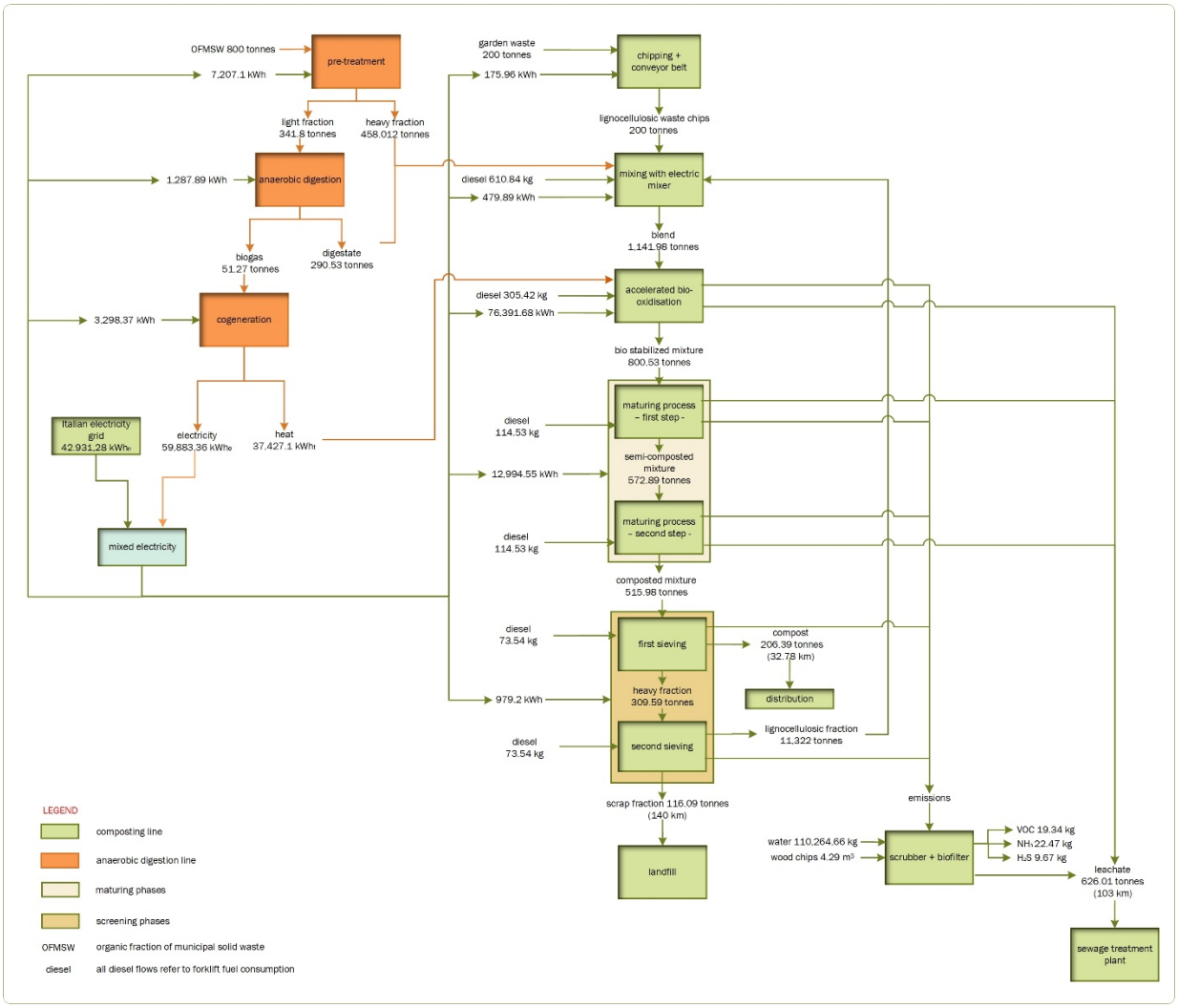

Fig. 2 System boundaries simplified scheme of option "B"- AD/Composting (only the emissions calculated by the Authors are shown; elaborated by the Authors).

2.2. LCA analysis of treatment options

The aim of the study is to identify the environmental hotspots of two OFMSW treatment options for a composting plant (before and after the introduction of an AD plant) in the Italian region of Abruzzo. Therefore, two LCAs were conducted following the ISO 14040 (2006) and 14044 (2006) standards. The considered function is the treatment of organic waste entering the plant and the compost production, whilst the FU is the treatment of 1,000 tonnes of organic waste. For both systems, the system boundary ranges from the organic material storage in the reception area of the facilities to the compost distribution, to waste disposal at landfill and the sterilisation and purification of wastewaters in a sewage treatment plant. In option "B", the energy production from biogas is used exclusively within the premises; it is thus not intended for the market. The data used in option "A" is predominantly primary and refer to 2015. When primary data were not available, reference was made to secondary data from the Ecoinvent 2.2 database (Ecoinvent Center, 2017). For the "B" option, data were obtained directly from the expansion project. Modelling was performed by using the SimaPro 7.2.4 software (PRé, 2010). The environmental impact assessment method used was ReCiPe Midpoint (Goedkoop *et al.*, 2009) with hierarchical perspective and global-level normalisation. The recycling fraction obtained from the screening process was excluded from the calculations as a closed loop case. Data on exhaust air treatment (air suction, scrubber and bio-filter) are included in the accelerated bio-oxidation phase; since it is the most active phase from a fermentation point of view, indeed, it produces the most significant amount of emissions.

3. Results and discussion

Through the characterisation results (Fig. 3) it can be noted that in the "A" option, the compost production phase assumes the highest values in 9 out of 18 impact categories: climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FEu), particulate matter formation (PMF), agricultural land occupation (ALO), natural

land transformation (NLT), water depletion (WD), fossil depletion (FD). The landfill phase (which includes the transport of scraps) prevails, however, in the remaining 9: marine eutrophication (ME), human toxicity (HT), photochemical oxidant formation (POF), terrestrial ecotoxicity (TE), freshwater ecotoxicity FE), marine ecotoxicity (MEc), ionising radiation (IR), urban land occupation (ULO), metal depletion (MD). In option "B" (Fig. 4), the stage of wastewater treatment (including transport) is more affecting for 8 categories (CC, OD, TA, POF, PMF, IR, MD, FD); this is followed by landfill, that prevails in 6 of them (ME, HT, TE, FE, MEc, ULO), and finally the compost production, which emerges in the remaining 4 (FEu, ALO, NLT, WD).

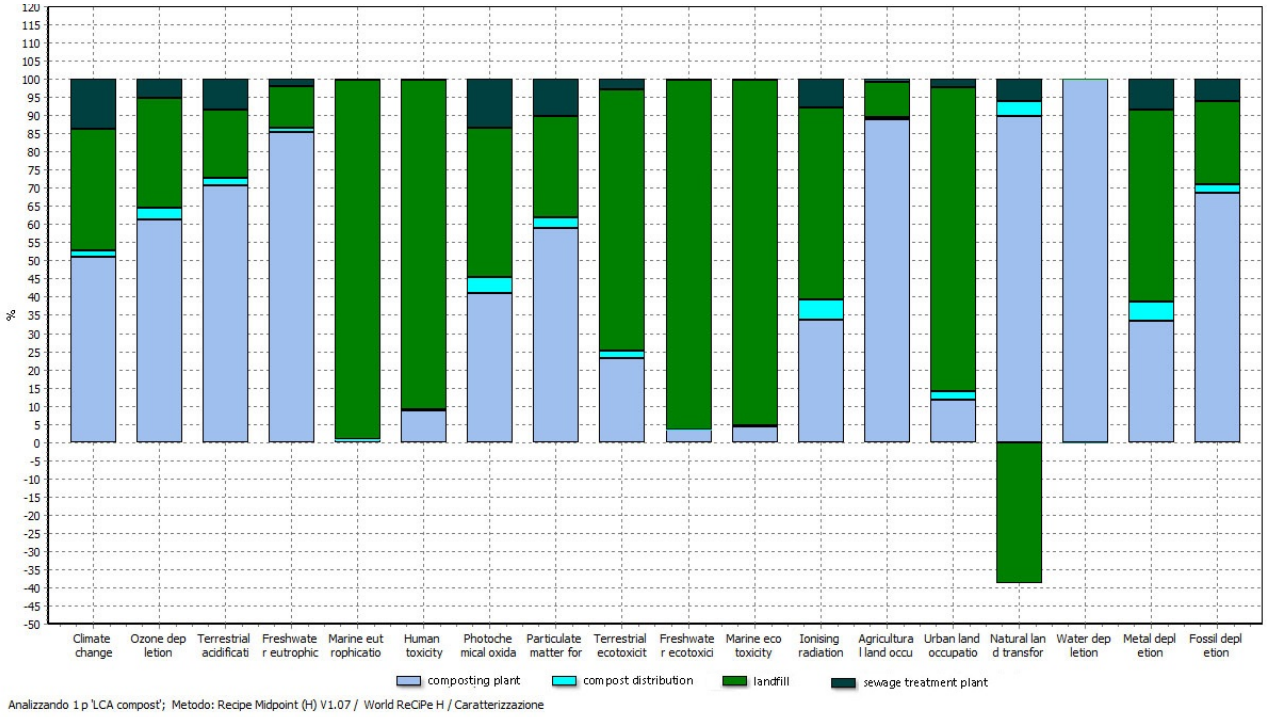

Fig. 3 Environmental profile of option "A" (characterisation results). The negative values refer to environmental credits, i.e., avoided impacts, whilst the positive values refer to environmental burdens (Source: SimaPro Software).

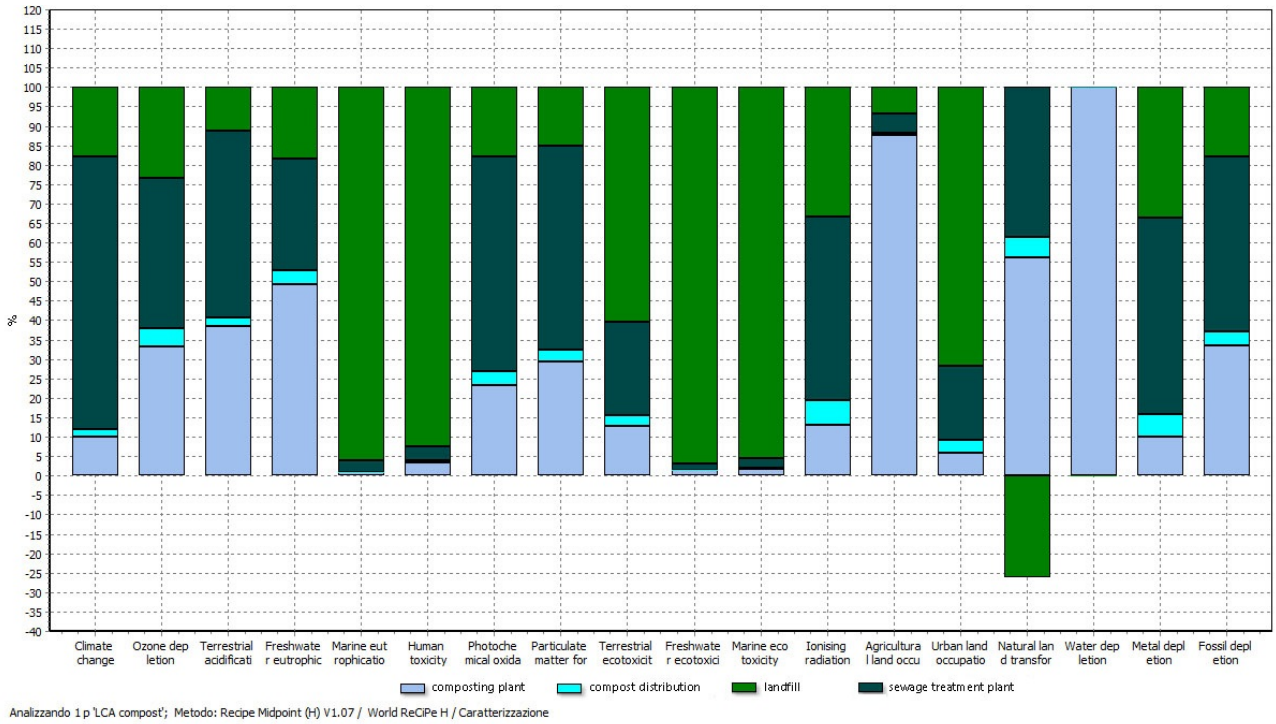

Fig. 4 Environmental profile of option "B" (characterisation results). The negative values refer to environmental credits, i.e., avoided impacts, whilst the positive values refer to environmental burdens (Source: SimaPro Software).

Tabs. 2a and 2b present the *impact scores* for each impact category in the two options.

Tab. 2a Impact scores for option "A" (characterisation). The figures in bold highlight the phases that contribute the most to the total value (Source: SimaPro Software).

Impact category	*Unit*	*Total*	*Composting Plant*	*Compost Distribution*	*Sewage Treatment Plant*	*Landfill*
Climate change	*kg CO_2 eq*	*91,647.09*	***46,786.44***	*1,642.831*	*12,563.21*	*30,654.6*
Ozone depletion	*kg CFC-11 eq*	*0.008071*	***0.004952***	*0.000257*	*0.000424*	*0.002438*
Terrestrial acidification	*kg SO_2 eq*	*389.9039*	***275.0826***	*8.287794*	*33.08476*	*73.44877*
Freshwater eutrophication	*kg P eq*	*10.53895*	***8.985303***	*0.132735*	*0.200814*	*1.220095*
Marine eutrophication	*kg N eq*	*1,338.375*	*9.42738*	*0.489678*	*4.648746*	***1,323.809***
Human toxicity	*kg 1,4-DB eq*	*80,234.61*	*7,014.22*	*173.3532*	*307.4928*	***72,739.55***
Photochemical oxidant formation	*kg NMVOC*	*309.5152*	*126.5237*	*13.76023*	*41.38581*	***127.8455***
Particulate matter formation	*kg PM_{10} eq*	*115.2431*	***67.7708***	*3.555418*	*11.78596*	*32.13093*
Terrestrial ecotoxicity	*kg 1,4-DB eq*	*14.6679*	*3.389139*	*0.282053*	*0.436979*	***10.55973***
Freshwater ecotoxicity	*kg 1,4-DB eq*	*4,069.954*	*139.8696*	*3.655491*	*6.934242*	***3,919.494***
Marine ecotoxicity	*kg 1,4-DB eq*	*3,467.457*	*153.291*	*4.766629*	*8.321409*	***3,301.078***
Ionising radiation	*kg U_{235} eq*	*2,977.518*	*998.9309*	*168.7173*	*235.2286*	***1,574.642***
Agricultural land occupation	*m^2a*	*1,082.816*	***961.767***	*5.6867*	*8.22805*	*107.1345*
Urban land occupation	*m^2a*	*1,119.288*	*131.9187*	*23.47174*	*26.14187*	***937.7555***
Natural land transformation	*m^2*	*8.511463*	***12.50829***	*0.596152*	*0.843058*	*-5.43603*
Water depletion	*m^3*	*1.18E+08*	***1.18E+08***	*5.776244*	*-73.2017*	*102.3083*
Metal depletion	*kg Fe eq*	*1,218.761*	*407.5972*	*62.41247*	*101.6039*	***647.1473***
Fossil depletion	*kg oil eq*	*23,485.99*	***16,130.66***	*566.6472*	*1,429.622*	*5,359.06*

Tab. 2b Impact scores of impact categories for option "B" (characterisation). The figures in bold highlight the phases that contribute the most to the total value (Source: SimaPro Software).

Impact category	*Unit*	*Total*	*Composting Plant*	*Compost Distribution*	*Sewage Treatment Plant*	*Landfill*
Climate change	*kg CO_2 eq*	*91,318.07*	*9,222.61*	*1,610.53*	***64,070.83***	*16,414.09*
Ozone depletion	*kg CFC-11 eq*	*0.005*	*0.0018*	*0.0002*	***0.002***	*0.001*
Terrestrial acidification	*kg SO_2 eq*	*351.54*	*135.36*	*8.12*	***168.73***	*39.33*
Freshwater eutrophication	*kg P eq*	*3.56*	***1.75***	*0.13*	*1.02*	*0.65*
Marine eutrophication	*kg N eq*	*738.8*	*5.78*	*0.48*	*23.71*	***708.84***
Human toxicity	*kg 1,4-DB eq*	*42,134.44*	*1,447.748*	*169.94*	*1,568.18*	***38,948.58***
Photochemical oxidant formation	*kg NMVOC*	*382.1*	*89.26*	*13.49*	***211.06***	*68.28*
Particulate matter formation	*kg PM_{10} eq*	*114.43*	*33.63*	*3.48*	***60.11***	*17.2*
Terrestrial ecotoxicity	*kg 1,4-DB eq*	*9.36*	*1.19*	*0.28*	*2.23*	***5.65***
Freshwater ecotoxicity	*kg 1,4-DB eq*	*2,168.37*	*30.72*	*3.58*	*35.36*	***2,098.7***
Marine ecotoxicity	*kg 1,4-DB eq*	*1,848.57*	*33.89*	*4.67*	*42.44*	***1,767.57***
Ionising radiation	*kg U_{235} eq*	*2,537.28*	*329.1*	*165.4*	***1,199.64***	*843.14*
Agricultural land occupation	*m^2a*	*846.54*	***741.64***	*5.57*	*41.96*	*57.36*
Urban land occupation	*m^2a*	*700.54*	*42.09*	*23.01*	*133.32*	***502.12***
Natural land transformation	*m^2*	*8.21*	***6.24***	*0.58*	*4.3*	*-2.91*
Water depletion	*m^3*	*1.1E+08*	***1.1E+08***	*5.66*	*-373.32*	*54.78*
Metal depletion	*kg Fe eq*	*1,028.254*	*102.38*	*61.18*	***518.17***	*346.52*
Fossil depletion	*kg oil eq*	*16,139.17*	*5,423.24*	*555.5*	***7,290.9***	*2,869.523*

Tabs. 2a and 2b contain the results of the characterisation scores for each of the environmental impact categories. They show that the most impacting phases are different for the two options. For option “A” it is landfill (including transport to it) and the composting process -- for the exclusive use of electricity deriving from the Italian grid, which is generated from fossil fuels for circa 60% (Di Maria and Micale, 2014) -- to be the most impacting phases. On the other hand, the sewage treatment plant (including transport) appears to be the most impacting phase for option “B”. The results of the normalisation are shown in Figs. 5 and 6. Both the OFMSW treatment options mainly affect three impact categories: HT, FE and MEc. Indeed, it can be observed that on a total score of 3,343.7 from "A" and 1,796 from "B", the three categories affect circa 91% and 90% respectively. Specifically, HT assumes 683.6 points for "A" and 358.99 for "B"; FE 940.16 points for "A" and 500.89 for "B" and MEc 1,435.53 points for "A" and 765.31 for "B".

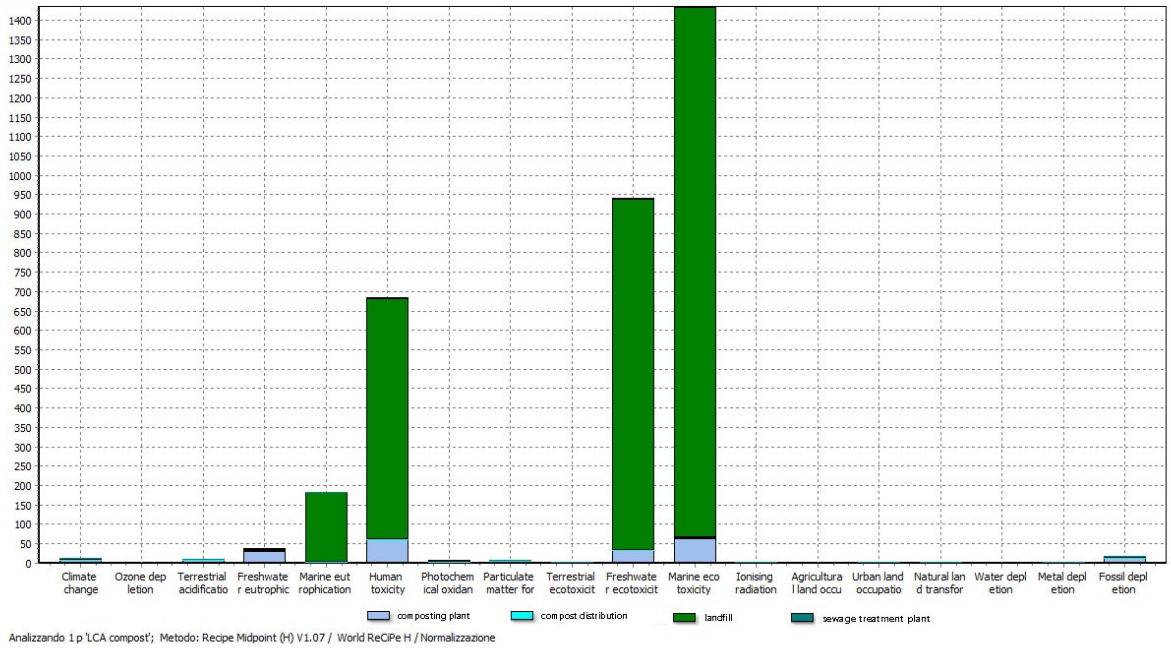

Fig. 5 Normalisation results for option “A” (Source: SimaPro Software).

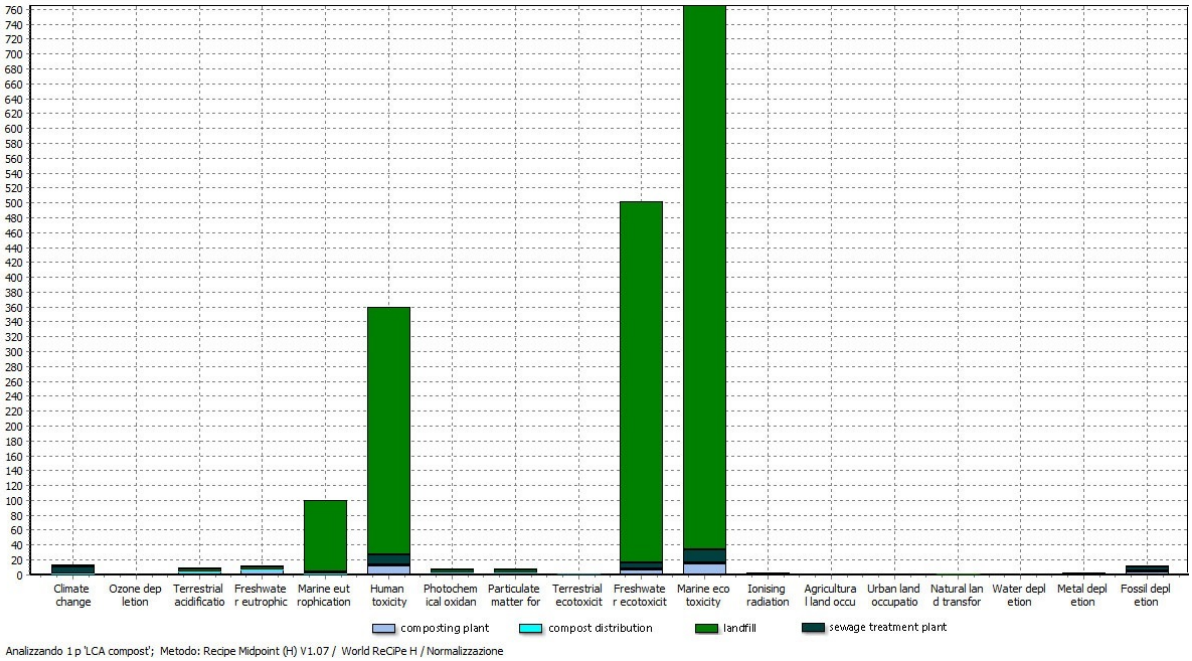

Fig. 6 Normalisation results for option “B” (Source: SimaPro Software).

Following the characterisation and normalisation results, the various processes are presented in Tabs. 3a, 3b and 3c in order of importance. This was performed for those processes that are responsible for the potential environmental impacts associated with the most affected impact categories (HT, FE and MEc). The results show that landfill disposal is the most responsible in all cases.

Tab. 3a Order of importance of the processes that are responsible for human toxicity (elaborated by the Authors).

Option A	*Option B*
1- landfill	*1- landfill*
2- Italian grid electricity consumption	*2- transport to landfill*
3- transport to landfill	*3- Italian grid electricity consumption*
4- diesel consumption for OFMSW internal movements	*4- diesel consumption for OFMSW internal movements*
5- compost distribution	*5- leachate treatment*
6- biomass disposal of the biofilter	*6- compost distribution*
7- leachate treatment	*7- use of filtrating biomass*
8- use of filtrating biomass	*8- compost production*

Tab. 3b Order of importance of the processes that are responsible for Freshwater ecotoxicity (elaborated by the Authors).

Option A	*Option B*
1- landfill	*1- landfill*
2- Italian grid electricity consumption	*2- transport to landfill*
3- transport to landfill	*3- Italian grid electricity consumption*
4- diesel consumption for OFMSW internal movements	*4- diesel consumption for OFMSW internal movements*
5- compost distribution	*5- leachate treatment*
6- leachate treatment	*6- compost distribution*
7- biomass disposal of the biofilter	*7- use of filtrating biomass*
8- use of filtrating biomass	*8- compost production*

Tab. 3c Order of importance of the processes that are responsible for marine ecotoxicity (elaborated by the Authors).

Option A	*Option B*
1- landfill	*1- landfill*
2- Italian grid electricity consumption	*2- transport to landfill*
3- transport to landfill	*3- Italian grid electricity consumption*
4- diesel consumption for OFMSW internal movements	*4- diesel consumption for OFMSW internal movements*
5- compost distribution	*5- leachate treatment*
6- leachate treatment	*6- compost distribution*
7- biomass disposal of the biofilter	*7- use of filtrating biomass*
8- use of filtrating biomass	*8- compost production*

In Tab. 4 the substances that are mainly responsible for the three most potentially affected impact categories are reported. They originate mainly from the landfill phase (transport and disposal of mainly plastic material). In Option "B", these substances undergo a reduction in terms of kg of 1,4-DB eq.

Tab. 4 Mainly responsible substances for the most affected impact categories (elaborated by the Authors).

Option A

Impact category	*Substance*	*Compartment*	*Sub-compartment*	*Unit*	*Total*
HT	*Lead*	*Water*	*groundwater, long-term*	*kg 1,4-DB eq*	*20803.20*

FE	*Vanadium, ion*	*Water*	*groundwater, long-term*	*kg 1,4-DB eq*	*1629.18*
MEc	*Vanadium, ion*	*Water*	*groundwater, long-term*	*kg 1,4-DB eq*	*1613.84*

Option B

Impact category	*Substance*	*Compartment*	*Sub-compartment*	*Unit*	*Total*
HT	*Lead*	*Water*	*groundwater, long-term*	*kg 1,4-DB eq*	*11138.90*
FE	*Vanadium, ion*	*Water*	*groundwater, long-term*	*kg 1,4-DB eq*	*872.63*
MEc	*Vanadium, ion*	*Water*	*groundwater, long-term*	*kg 1,4-DB eq*	*864.41*

Tab. 5 summarises the main information and findings for both options.

Tab. 5 Main information and findings for options "A" and "B".

	Option A	***Option B***
Scenario	*current*	*future*
Type of biomass treated	*OFMSW + garden waste*	*OFMSW + garden waste*
Type of process treatment	*composting*	*AD/composting*
Output	*compost*	*biogas and compost*
Environmental hotspots	*compost production* *scrap landfilling*	*sewage treatment plant*
Most affected impact categories	*human toxicity* *freshwater ecotoxicity* *marine ecotoxicity*	*human toxicity* *freshwater ecotoxicity* *marine ecotoxicity*

Therefore, following the LCIA normalisation, the option which receives the lowest score for almost all impact categories is the "B" option. On the other hand, the "A" option is preferable only for the "Photochemical Formation of Oxidants" category with 6.31 points (compared to 7.79 for "B"), which depends on the higher quantities of leachate treated in option "B" and related transport to the sewage plant. In option "A", the phases that mainly affect the result are waste disposal (including transport) and compost production. In the other case, however, the disposal of wastewaters (including transport) is the most significant phase.

To sum up, this study showed that the best treatment method for organic waste deriving from separated collection seems to be the anaerobic/composting digestion solution, obtaining, in general, lower scores when analysed in parallel to the sole composting option. The only impact category that has a higher score within the "B" option is the photochemical formation of oxidants. From the interpretation of the results, therefore, the advantage of option "B" appears to be related to the production of biogas, as confirmed by Neri *et al.* (2018). This solution allows the plant to depend on the Italian electric mix to a lesser degree, which is mainly related to fossil resource consumption. In addition, the issues raised by Di Ciaula *et al.* (2015) on the possibility of finding pathogenic organisms for humans and plant species in the digestate would be solved in this case by the adoption of a subsequent stabilisation of the product through composting. The study outcome confirms what emerged in the systematic review (Mancini *et al.*, 2017a), where the energy recovery of OFMSW appeared as the preferred option in most of the analysed articles. In particular, in the case under study, as in Khoo *et al.* (2010), the results show that the only impact category to have a higher value for AD is POF. On the other hand, Thyberg and Tonjes (2017) state that the AD/composting scenario has better results for all the analysed categories except for marine eutrophication. In addition, a similarity can be observed with the study of Takata *et al.* (2013), where electricity consumption (national power grid) of the composting processes (option "A") and wastewater treatment for AD/composting (option "B") are the processes mostly contributing to climate change-related emissions. However, in several LCA analyses the compost is often considered only as a fertiliser (e.g., in Martínez-Blanco et al., 2008), even though it possesses a number of additional peculiarities that act on aspects of equal importance, such as soil quality

(organic matter, water content and salinity) or erosion (Martínez-Blanco et al., 2008). It has to be noted that the synthetic production of N based fertilisers is also an energy intensive process [Zabaleta and Rodic, 2015 in (Combo et al., 2018)]. Hence, the substitution of N recovered from waste for N-fertilizers could potentially contribute to climate change mitigation (Cobo et al., 2018). Finally, the compost has also an important role as a carbon sink, because it is considered to be a long-term carbon storage (Bong *et al*., 2017).

The negative value assumed by the natural land transformation impact category at the landfill stage may be interpreted as suggested by Schryver and Goedkoop (2009), who state that the transition from a non-natural soil (such as landfill) to a natural one (forest) assumes a negative characterisation factor. Indeed, regarding the landfill, the data of the Ecoinvent database was considered, in which it is envisaged that after 150 years of activity, the landfill will be covered and there will be vegetation (in particular, a forest).

4. Conclusions

LCA is a robust and standardised methodology that appears to be privileged for its capability to include multiple environmental categories, whilst avoiding the so-called burden shifting between them. This article presented a parallel analysis of the environmental impacts of two types of OFMSW treatment techniques by implementing this methodology. The results confirmed the general trend that was found in the literature, according to which the integration of AD with composting may have a better environmental performance when compared to the sole composting solution. Indeed, option "B" received lower normalised scores than option "A". The company under study would thus have the opportunity to accept a larger amount of OFMSW and reduce the external energy input thanks to the electricity and heat production.
A few critical issues emerged, mainly related to the phase of transport and landfilling of the scrap fraction, which has a significant role on the most affected impact categories; this would hopefully help the company to orientate future investment-related choices by working upstream and avoiding end-of-pipe solutions. Indeed, it should be considered that the fraction of non-compostable material in the facilities is mainly made up of plastics and of 23% of traditional plastic bags, despite the ban of non-biodegradable plastic bags provided for by the Italian regulation (GURI, 2012). As the presence of such fractions may depend on the quality of the incoming material, action should be taken to improve the effectiveness of source-separated collection made by households through the development of synergies between public authorities, various local entities and treatment facilities.
Considering the positive outcomes of the LCA analyses on the effects of biomethane production from the upgrading of biogas obtained from OFMSW treatment, future developments may include a new LCA study for the same facilities, which would consider the option of biomethane production for road transport. In this way, the most important impacts (identified via this study), linked to the transport of the scrap fraction to landfill and of the wastewater to the treatment plant, could be reduced. This choice would also be in line with recently issued regulation (EP/EC, 2009; MiSE, 2018). Finally, future developments may also include an integration of the results with economic (via life cycle costing) and social (via social life cycle assessment) issues, which is considered important in order for all three pillars of sustainability to be analysed and discussed.

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