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SUSTAINABILITY ASSESSMENT OF TWO DIGESTATE TREATMENTS: A COMPARATIVE LIFE CYCLE ASSESSMENT

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Abstract

Digestate derived from the anaerobic digestion of biowaste is a nutrient-rich substance whose direct use on land is not permitted by the Italian Legislation. The possibility of recovering its nutrients can be given by the processes of stabilisation and sanitation required by the Italian Legislation. Among these processes, composting and calcium hydrolysis with neutralization (CHN) permit to obtain useful soil improvers like compost and defecation gypsum (DG). In this paper a gate-to-gate Life Cycle Assessment (LCA) of these two processes is performed to evaluate their relative environmental sustainability, by using the ReCiPe H midpoint and endpoint impact assessment methods. The functional units (FUs) used in this analysis are one tonne of digestate treated by each process, and the amount of compost and DG necessary to amend one hectare of maize cultivation. Data used in the assessment were collected from plants located in Northern Italy and were referred to one year of operation. The processes of transport and spreading on land of the final products were not considered. The results of both the analyses show that CHN is the process with the largest environmental impacts, mainly due to the use of chemicals (i.e., sulfuric acid and calcium oxide). For both processes and FUs, the most impacted midpoint categories are Natural land transformation, Marine ecotoxicity and Freshwater ecotoxicity. Among the endpoint categories Resources is the most impacted one (followed by Human Health and Ecosystems), for both FUs, although showing larger differences for the agronomic use.

Key words: anaerobic digestion, circular economy, digestate treatment, LCA, sustainability assessment

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1. Introduction

In Italy the number of mechanical-biological processes for the urban waste treatment, before their definitive disposal or recovery, is increased in last years. In 2017, 340 out of 644 urban waste treatment plants were dedicated to the treatment of Organic Fraction in Municipal Solid Waste (OFMSW), 130 to mechanical or mechanical-biological treatment and 123 to landfills, while the others consisted in incinerators and industrial co-incinerators (ISPRA, 2018). During the last ten years, anaerobic digestion (AD) was implemented in several wastewater treatment plants as co-digestion of the OFMSW and waste activated sludge (WAS) (Tyagi et al., 2018). This approach allows both to increase wastewater treatment efficiency and to optimize the energy recovery. The AD liquid effluent, obtained after solid-liquid separation, is usually recycled back into the wastewater treatment plant, while the solid part is sent mainly to composting plants.

Considering the constant increase of urban waste production and consequently the increase in the amount of organic fraction sent to biological treatments, finding appropriate and sustainable processes to manage the digestate generated by AD of biowaste is urgently needed. In Italy, 55% of organic waste is treated by composting, 5% by AD and 40%

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by combined aerobic/anaerobic treatment. Among the waste sent to composting, 33% is composed of green organic materials, 50% of OFMSW, 12% of sewage sludge (SS) and the remaining 8% of other waste including digestate from AD (ISPRA, 2018).

To address the goals of the European Union "Circular Economy Action Plan" (EC Directive, 2015a), and the proposal of the European Commission on waste management (EC Directive, 2015b), the use of digestate as fertilizer has become an interesting practice to both reduce the amount of waste to landfill and close the nutrient cycles.

In Italy, the practice of spreading sewage sludge on agricultural land is widely adopted (Collivignarelli et al., 2015), as well as of spreading digestate deriving from the AD of biomass (agricultural, zootechnical, etc.) that can be directly applied on field or used as basis for fertilizers' production (DM, 2016). In the case of digestate derived from AD of biowaste this direct use is not permitted by the Italian Legislation as the digestate needs further processes of stabilization and sanitation (L.D., 2010) to inactivate pathogens for its safe release.

Currently, in the European Union a common regulatory framework that defines the general rules and guidelines for the sustainable management of digestate produced by anaerobic treatment of organic waste does not exist. In order to provide the scientific background in support of legislative decisions, it is therefore crucial to assess the potential environmental impacts of the technological processes related to different management scenarios of this by-product.

Currently, in Italy, digestate from biowaste can be treated by several processes; the main alternatives are: treatments for organic soil improvers' production, like composting and calcium hydrolysis; heat treatments, like incineration and pyrolysis for energy and biochar recovery; landfilling (Oldfield et al., 2018, Vázquez-Rowe et al., 2015); and processing in wastewater treatment plants (Di Maria and Sisani, 2019). Among these technologies, calcium hydrolysis with neutralization (CHN) is adopted to produce the so called "defecation gypsum" (DG), usable as soil improver and alkaline-controller, while composting leads to the production of compost.

Several LCA studies analysed the compost production (as result of biowaste treatment) and its land application, also as AD post-composting step (Bernstad and la Cour Jansen, 2011; Blengini, 2008; Cremiato et al., 2018; De Feo et al., 2016; Di Maria et al., 2016; Di Maria and Micale, 2015; Jensen et al., 2017, Neri et al., 2018), while no studies, to the best of our knowledge, can be found in the literature about DG production.

This paper contributes to the environmental impact assessment of digestate treatments, filling the gap in the analysis of the DG production and comparing its environmental performances with the more known and widely adopted composting process.

2. Material and methods

2.1. Goal and scope definition

In this paper a preliminary analysis of the potential environmental impacts at a global scale of composting and CHN of dehydrated digestate from biowaste is performed, by using the LCA (Life Cycle Assessment) method according to the ISO 14040 (2006) and ISO 14044 (2006) standards. This analysis was performed to evaluate the environmental performance of these two processes, and consequently understand which is the best alternative for the digestate treatment and which are the phases, for each process, most impacting human health and the environment.

The processes considered are: composting performed by the Energia Territorio Risorse Ambientali (ETRA) S.p.a. plant located in Veneto Region (Italy), where dehydrated SS coming from the civil wastewater treatment plant is processed together with green organic materials; and calcium hydrolysis performed by a plant located in Lombardy Region, treating SS and dehydrated digestate. In the LCA analysis, dehydrated SS and dehydrated digestate were assumed to be comparable, as supported by the physico-chemical characterisation results presented in Section 3. The LCA performed adopts a "gate-to-gate" approach. In fact, since the main input materials for both plants are coming from different locations (e.g. green organic materials collected in different villages) or treatment plants, their production was not included in the analysis, as well as the transportation and spreading phases, which are assumed to be similar for both compost and DG and not providing a relevant contribution. In fact, previous studies (Bernstad and la Cour Jansen, 2011; Blengini, 2008) showed that transport operations play a minor role in the overall environmental impact (e.g., providing the lowest contribution, except for Ozone layer depletion, in Blengini (2008), due to the fact that the involved distances are usually reasonably short (an average of 25 km). As far as the construction of the plant is concerned, it was not included in the analysis because both the plant buildings have a long lifetime and consequently its contribution to the environmental impact assessment of one year of plants operation would not be so relevant. In addition, data about maintenance operation of the plants were not available and therefore they were not included in the analysis. Data on soil occupation for the composting plant were also not available since the composting process is integrated into a much larger wastewater treatment plant area and therefore they were not included in the analysis (although the information was available for the CHN plant). Finally, in the composting process the production of fine compost was not considered as it is optional.

The Functional Unit (FU) of this analysis is one tonne of digestate treated by each plant during one year of plant operation. In addition, to assess the environmental performance of the soil amendments produced, the amount of product necessary to improve one hectare of maize cultivation was considered as second FU. Primary data of material, fuels and energy consumptions were collected directly from the plants or calculated from assumptions made by the authors, while for secondary data the database Ecoinvent v 3.3 (Wernet et al., 2016) was adopted. Data were elaborated by means of SimaPro 8.3 software and the selected treatment options were compared following the ReCiPe v.1.13 assessment method (Goedkoop et al., 2013), that quantifies the environmental impacts on 18 categories at the midpoint level, and 3 at the endpoint level. This method represents the highest level of convergence with the ILCD recommendations (ECJRC-IES, 2011). The midpoint approach was adopted in this study to evaluate the 18 impact categories individually under a Hierarchist perspective, which consider average conditions in terms of time horizon, pessimistic or optimistic point of view, type of effects considered etc.

Although normalisation is an optional step under ISO 14044:2006, it was applied to the midpoint results in order to support the interpretation of the two processes' impact profiles. This additional step is frequently adopted in other LCA studies on composting processes (e.g., in Di Maria et al. (2015) and (2016)). Normalization reports the characterized results of the impact categories at the same scale and consequently it allows evaluating the relative magnitude of potential impacts. The normalization set selected in this study is Europe ReCiPe H, 2000, which refers to the environmental impacts of Europe in 2000 (Sleeswijk et al., 2008).

3. Case studies

The physico-chemical characteristics of the dehydrated digestate treated by the DG production plant are reported in Table 1 together with the characteristics of the dehydrated SS treated by the composting plant. Since the two materials show similar characteristics, we could assume in the LCA analysis that the same composting process used to treat SS can treat digestate without significantly affecting input and output parameters.

3.1. The composting plant

The composting plant analysed in this study is part of the ETRA S.p.a. biotreatment centre located near Padova, in Northern Italy, where urban wastewater is treated and the derived SS is composted together with branches and green organic material, reaching a total amount of treated material of approximately 20 000 tonnes per year. For the purpose of this study, that is to analyse the treatment processes of digestate, SS was replaced by digestate (as justified by Table 1). Therefore, we considered branches, green organic materials and digestate as input materials for this plant.

The composting process (Fig. 1) starts with the storages of the digestate arriving to the plant, which occurs in a depressed shed, where the exhausted air is extracted by four fans. This building has a maximum capacity of 1 000 m^3 and is also used for the storage of mature compost and the shredded green organic material before its processing. Digestate is combined with green organic materials to reach the C:N ratio (25:1-30:1) and moisture content (~60%) optimal to the composting process.

In the first phase, called "accelerated bio-oxidation", the degradation of organic matter takes place thanks to the accelerated metabolism of decomposing microorganisms, with the consequent production of odorous emissions and heat. In the centre of the bio-oxidation shed the input material is loaded with mechanical shovels, alternating layers of digestate and lignocellulosic material in appropriate ratio, according to the chemical composition of digestate. During this phase air is supplied in the mixture through nine fans and overturning is performed with an automatic turning machine. The high temperature reached by the decomposing materials (~70°C) allows to sanitize the mixture by removing weed seeds and pathogenic microorganisms. The mixture is also ventilated to remove the excess of moisture, by means of some grids placed on the floor of each lane, under the piles.

The air removed from the low-pressure area and the bio-oxidation locals is treated by biofilters before being emitted in air. These filters are made of wood chips of 20-40 mm and of wooden root of about 40 cm. These materials are also enriched in granular lime. When the bio-oxidation process ends, after thirty days from its beginning, the fresh compost is transferred to an external lot through a mechanical blade machine and the screening phase takes place. This phase consists in the mechanical separation of organic particles with diameter lower than 20 mm (i.e., undersize materials), from the remains (i.e., oversize materials), consisting on pieces of wood and small amount of plastic that is typically used for landfill coverage.

The undersize material continues its processing in the maturation phase, which occurs outdoors for eight weeks. The fresh compost is accumulated to favour the aeration and the outflow of rain. Periodically, the compost in maturation is analysed in its content of humidity, pH and temperature until its complete maturation. Another additional (and optional) step is the refining process, where a vibrating screen with 10 mm meshes separates the fine compost, that can be sold as improver for plant nurseries, farms or individuals, from the coarse one.

3.2. The CHN plant

The CHN plant analysed in this study is located in the Lombardy Region, in Northern Italy, and it carries out the recovery of a total amount of about 50 000 tonnes per year of SS and digestate, converting them into DG.

Table 1. Physico-chemical characteristics of the dehydrated digestate treated by the calcium hydrolysis plant and the dehydrated SS treated by the composting plant. (TKN=total Kijendhal Nitrogen, TP= total phosphorus COD = Chemical Oxygen Demand, TOC = Total Organic Carbon, DM = Dry Matter)

Parameter	*Unit*	*Dehydrated digestate*	*Dehydrated SS*
pH		8.17	7.22
DM (%)	%	23.31	21.58
TKN	%DM	5.33	5.79
NH_4^+	%DM	0.86	0.13
TP	%DM	2.40	2.02
COD	%DM	80.39	83.31
TOC	%DM	42.09	37.41

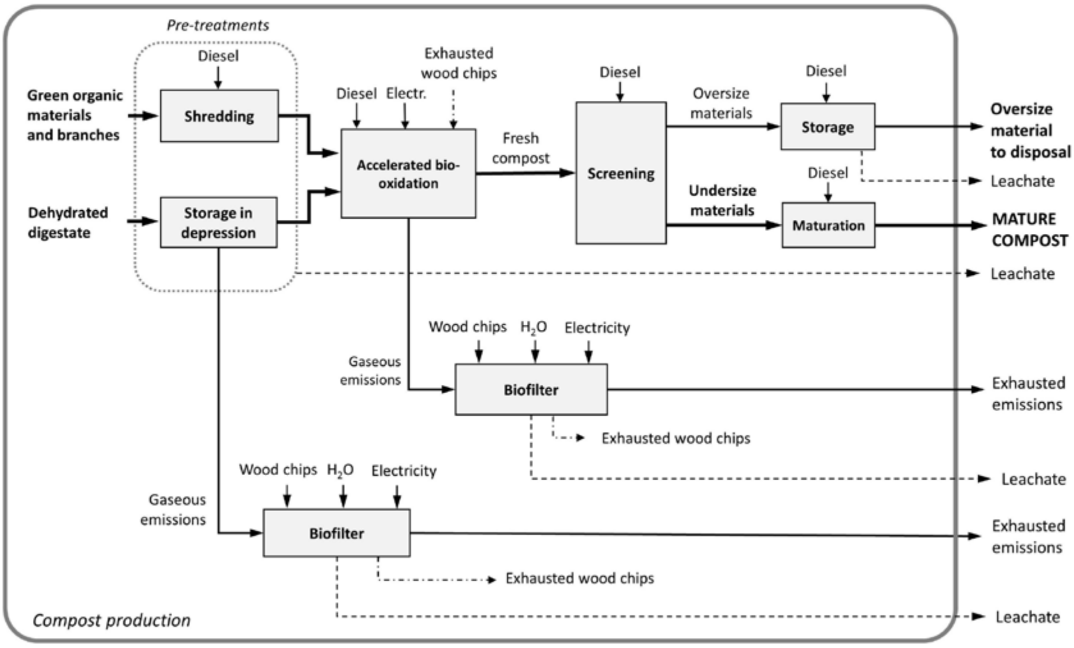

Fig. 1. Flow diagram of composting process including the emission treatment

This product is composed by CaO and SO_3, for 20% and 15% of the total dry weight respectively, and its use is recommended before the soil's ploughing operations as soil improver, calcium and sulphur provider and alkalinity corrector. The SS (around 95% of the total input) and the dehydrated digestate (about 5% of the total) are the main waste treated in this plant and are always checked for physico-chemical characteristics before starting the treatment and during the process.

In Fig. 2 the flow diagram of the DG production phases is reported. The matrices accepted by the plant are temporary stocked in closed tanks equipped with suction systems and mixed by an excavator. If necessary, a small percentage of liquid sludge and water is added to fluidify the mixture. Afterwards, the mixture is transferred by a telescopic blade in another tank where calcium sulfide ($CaSO_4$) starts the alkaline hydrolysis process.

The alkaline chemical products are then neutralized by the hydrochloric acid (HCl). At the end of this process the DG is ready and is transferred by gravity in another storage tank where it loses moisture by evaporation. If the lot is not compliant to the parameters fixed by the company, it will be processed again. In order to contain the emissions from the chemical processes that occur during the DG production, all phases take place in closed, low pressure areas. The intake air is conveyed in a dedicated treatment emission plant that consists in a wet scrubber, an expansion chamber and a biofilter. The main pollutants intercepted are ammonia, odorous emissions, volatile organic compounds and HCl.

3.3. Inventory

Data input and output of the systems depicted in Fig. 1 and Fig. 2 include energy and matter flows for each process unit (Tables 2, 3), that were collected directly from the plants or estimated by the authors. Water consumption by composting biofilters have been estimated from the consumption of water by DG production's biofilters. All phases of both processes take place in closed buildings and therefore the only emissions included were those coming out from biofilters, which were considered as addressing the emissions legal limits (L.D., 2006).

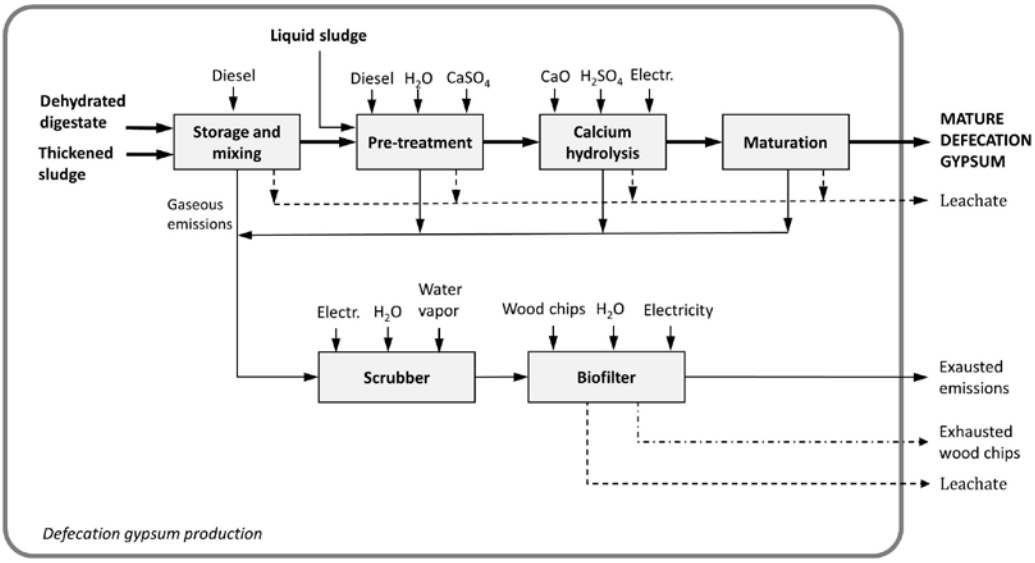

Fig. 2. Flow diagram of DG production including the emission treatment

The product quantities considered for the impact assessment according to the second FU were those necessary to amend one hectare of maize cultivation, by considering their production only (not including their transport and spreading). The amount of compost considered was obtained by agronomical tests on Italian sites, that are consistent with average values present in the literature (www.venetoagricoltura.org). Regarding the DG, the value considered came from a specific test made by the DG producer (Agrosistemi S.r.l., private communication) as in literature, to the best of our knowledge, there are not studies on this product and further analysis would be needed to better understand its amendment power and security. From the collected data (reported in Table 4), it emerged that about the same amount of compost and DG is necessary to amend one hectare of soil for maize cultivation, although DG does not provide any contribution to phosphorous and potassium content, thus requiring additional input of these mineral fertilizers.

However, it must be noted that sometimes also amendment with compost requires an addition of these minerals since the compost nutrients content strongly depend on the characteristics of the materials used as input to the composting process.

4. Results and discussion

Fig. 3 reports the LCA comparison of compost and DG production, calculated by using the ReCiPe Hierarchist midpoint method with normalization of results. The comparison shows that the highest environmental burden is associated to DG production, where Natural land transformation, Marine ecotoxicity and Freshwater ecotoxicity are the most impacted categories. This result can be explained by the use of some chemicals (i.e., sulfuric acid and calcium oxide) in the CHN process, which cause the most relevant contribution to the three impact categories (Figs. 4-6).

Table 2. Total annual input and output of composting process including the emission treatment

Input	***Amount***	***Unit***
Dehydrated digestate	3 460	tonnes year^{-1}
Green organic materials and branches	15 720	tonnes year^{-1}
Diesel	40 080	L year^{-1}
Electricity	1 070 195	kWh year^{-1}
Wood chips	1535	m^3 year^{-1}
Water	55.5	m^3 year^{-1}
Output	Amount	Unit
Compost	5 560	tonnes year^{-1}
Dust	0.27	mg Nm^{-3}
Ammonia	0.57	mg Nm^{-3}
Sulfuric acid	0.57	mg Nm^{-3}
VOC	0.11	mg Nm^{-3}

Table 3. Total annual inputs and outputs of defecation gypsum production including the emission treatment

Input	*Amount*	*Unit*
Thickened sludge	47 500	tonnes year^{-1}
Dehydrated digestate	2 500	tonnes year^{-1}
Liquid sludge	1 280	tonnes year^{-1}
Diesel	18 500	L year^{-1}
Electricity	317 100	kWh year^{-1}
Calcium sulphate	2 500	tonnes year^{-1}
Sulfuric acid	7 500	tonnes year^{-1}
Calcium oxide	7 500	tonnes year^{-1}
Wood chips	160	m^3 year^{-1}
Water	1 300	m^3 year^{-1}
Output	**Amount**	**Unit**
Mature defecation gypsum	31 135	tonnes year^{-1}
Water vapor	14 650	tonnes year^{-1}
Ammonia	0.6	mg Nm^{-3}
VOC	1.5	mg Nm^{-3}
Mercaptans	0.5	mg Nm^{-3}
Hydrogen sulphide	0.1	mg Nm^{-3}
Exhausted wood chips	100	m^3 year^{-1}

Table 4. Quantity of compost and DG necessary to amend one hectare of soil for maize cultivation and respective nutrients content. Values in brackets are from additional mineral fertilizers

Soil improver	*Amount (kg/ha)*	*N (kg/ha)*	*P_2O_5 (kg/ha)*	*K_2O (kg/ha)*	*Yield (kg/ha)*
Compost	33 000	116	243	232	10000
Defecation gypsum	32 400	227	(0.79)	(0.4)	10000

On the other hand, for the composting process the impacts to these categories, despite being much lower than those of DG, are linked to the electricity consumptions of fans, windrows and grinder. Comparing the composting process and the anaerobic digestion of biowaste, Blengini (2008) shows high environmental impacts for the categories Acidification and Nutrient enrichment caused by the biogenic emissions from the aerobic degradation process and remarkable Gross Energy Requirement of compost process. However, as highlighted in the review by Bernstad and la Cour Jansen (2012) about LCA of different treatment systems, estimated impacts vary largely among different studies, due to the different setting of the system boundary methodology (e.g., including or not transport), the selected metodology (e.g., different impact assessment methods, including or not avoided impacts), and the variation on input data (e.g., the characterization of the treated biowaste). These considerations lead to some difficulties in comparing our study with others in the field and suggest the need to estabilish more detailed guidelines to improve such situation.

To assess the environmental performance of the two processes in relation to the amendment power of compost and DG, the amount needed to improve one hectare of maize cultivation was considered. The impact profile (Fig. 7) shows again that for the category Natural land transformation the higher impact is clearly associated to DG, while for other categories like Freshwater eutrophication, Freshwater ecotoxicity and Marine ecotoxicity the production of compost is providing a slightly higher contribution compared to DG. Finally, looking at the endpoint impacts on Human health, Ecosystems and Resources (Fig. 8), DG production shows the higher impacts according to both our FUs.

However, it must be noted that these are the results of a preliminary "gate-to-gate" LCA, where processes that occur before and after the production of compost and DG (like construction and maintenance of the plant and transportation of waste material) were not considered. By expanding the systems' boundaries, maintenance of the plant could play a relevant role in the generation of environmental impacts while the contribution of transportation of waste material to treatment plants should be negligible if the digestate treatment takes place in the proximity of its production (which is usually the case as reported by Bernstad and la Cour Jansen (2011) and Blengini (2008)).

Moreover, results could be affected by including additional information which were not available to the authors. The most relevant case would be the possibility to consider the portion of land covered by each phase of the two treatment processes. In fact, it is known that for the composting process large areas are usually needed and this could impact the Natural land transformation category in favour of CHN process.

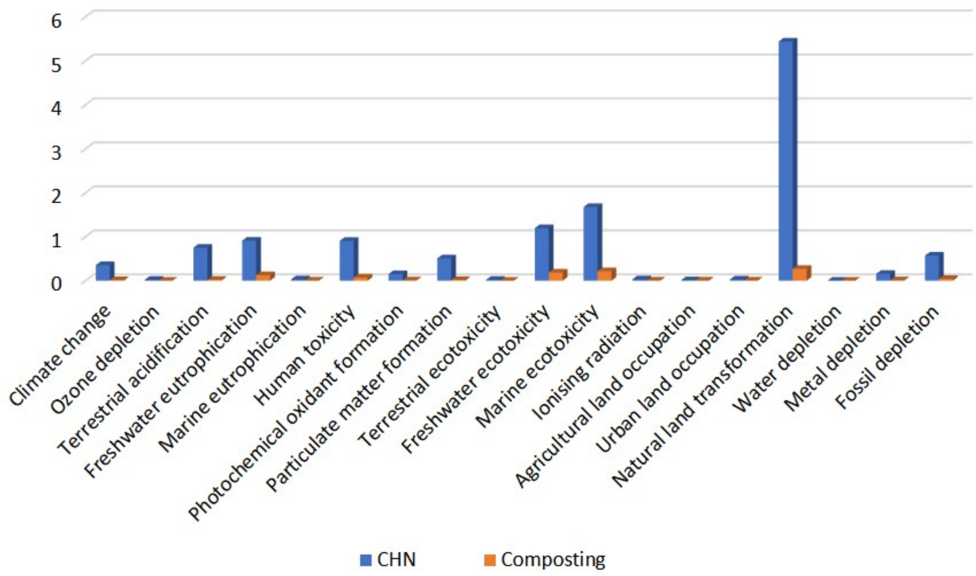

Fig. 3. Comparison of normalizated results for the treatment of 1 tonnes of digestate with CHN and composting processes

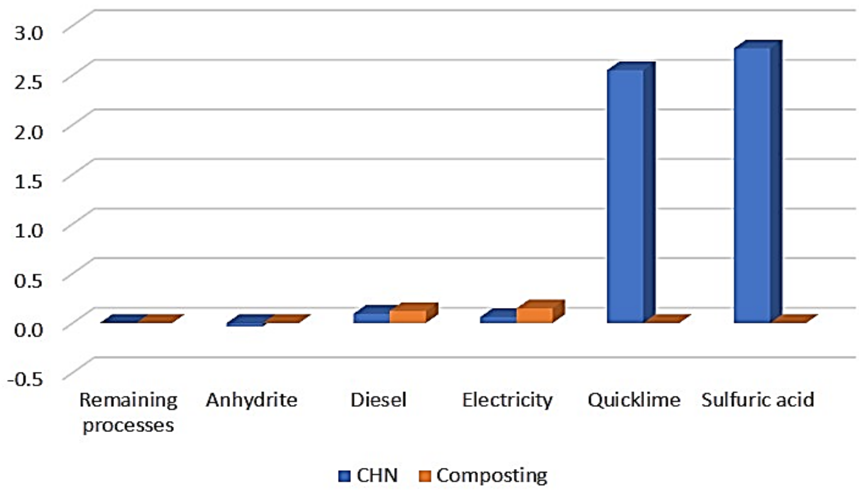

Fig. 4. Most impacting processes on Natural land transformation category

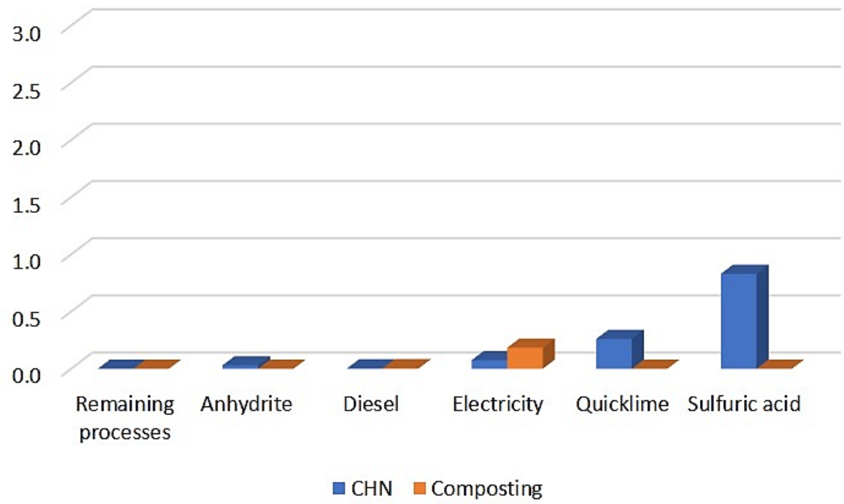

Fig. 5. Most impacting processes on Freshwater ecotoxicity category

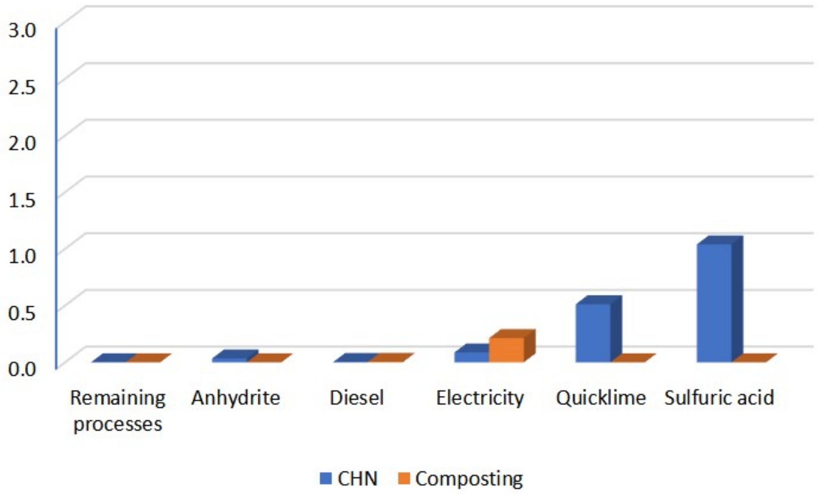

Fig. 6. Most impacting processes on Marine ecotoxicity category

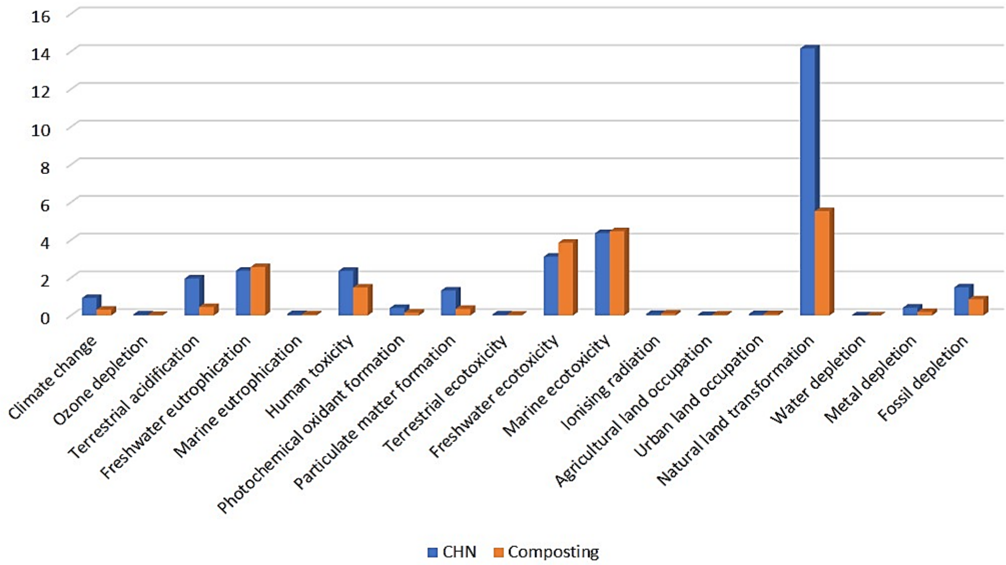

Fig. 7. Comparison at midpoint level between CHN and composting, according to the agronomic utilization

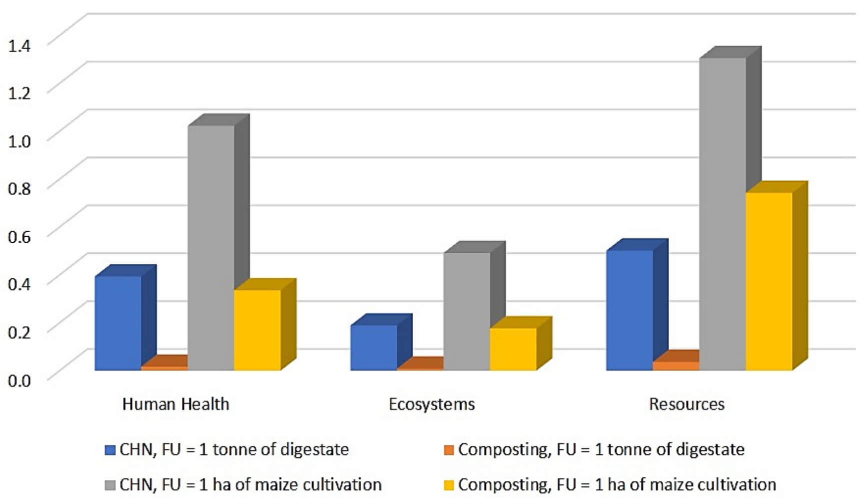

Fig. 8. Comparison at endpoint level between CHN and composting, according to the two FUs used in the study

5. Conclusions

In this paper the environmental impacts of the treatment of waste-digestate by composting and CHN processes are reported. These processes are suitable alternatives to landfill or incineration, and lead to the production of useful soil improvers (i.e., compost and DG).

Although the gate-to-gate LCA results indicate that CHN is responsible for higher environmental impacts compared to composting at both midpoint and endpoint levels and according to both our FUs, the following additional observations can be made. The composting process considered in this study lasts about three months, while the CHN process takes place in about thirty days.

This means that, with the same processing capacity, CHN can stabilize a higher amount of organic waste in the same time frame, thus speeding up the overall waste treatment process and therefore leading to an economic benefit.

On the other hand, improvements could be envisaged also for the composting process. Indeed, digestate is the effluent of an anaerobic stabilization process intended to remove the organic substance by converting it to carbon dioxide and methane; therefore, its characteristics can vary significantly as the input matrices and the operating parameters set (e.g. retention time and organic load) change. This means that knowing the characteristics of the specific digestate would allow to optimize the composting treatment phases in terms of duration as well as materials and energy use.

As an example, the duration of the oxidation phase could be reduced according to the quantity of putrescible matrix in the digestate. Therefore, an enhanced monitoring of the physico-chemical and biological parameters of the digestate along with the possibility to set up flexible composting processes, tailored to the input needs, would allow to end up with more environmentally sustainable solutions.

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