Food waste anaerobic digestion in Umbria region (Italy): scenario analysis on the use of digestate through LCA

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Abstract. The project irexfo LIFE16 deals mainly with food waste and expired food prevention and reduction, but also with its valorization in biogas plants. Due to legal aspects the cycle of food waste needs to be closed returning the anaerobic digestate to the soil and so providing fertilizer for the cultivation and production of new crops. This is not possible at the moment in Italy because of the Decree of the 25th February 2016 on the disposal of digestate produced from raw materials which are not considered biomasses. The EU Regulation of 2019/1009 of the European Parliament and of the council of the 5th of June 2019, identifies some Component Materials Categories (CMCs), which can be considered as fertilizers; among them we find digestate other than fresh crop digestate, which includes digestate produced from bio-waste and another category on food industry wastes. For this reason, it is meaningful to compare the two possible alternatives: use of food waste digestate as it is in the field and use of food waste digestate after composting it (as currently required by the Italian law).

1 Introduction

According to the European Biogas Association and the Italian Consortium for Biogas (CIB), Italy had 1,555 biogas plants in 2017 [1]. Italy is second only to Germany in Europe for the number of biogas plants and so also for the production of digestate. An interesting report prepared by Ramboll, Peter Frisk Associates and Wood consultants, named "Digestate and compost as fertilizers: Risk assessment and risk management options" [2], takes into consideration: market analysis; substance identification; risk assessment; and risk management options.

Dealing with the market it is estimated that around 180 million tons of digestate are produced in the EU28 per year, almost half of this in Germany. The Italian digestate production is estimated to be about 30 Mt. If we compare those data with the production of compost, we see that the European production is about 17.3 Mt and the Italian production is about 2.2 Mt. So, it appears that digestate production is 10 times higher than that of compost. The main materials used to produce compost are represented by green waste and

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separated organic fraction of municipal waste, a smaller part of the produced compost is obtained also from sewage sludge.

According to the analysis presented in the report, 7 polluting substances have been identified, such as:

- Heavy metals (Cd, Ni, Pb, Cu, Zn, Hg);
- 17α-ethinylestradiol;
- Polychlorinated Biphenyl (PCBs, in particular PCB28);
- Dioxins and furans (2,3,7,8-Tetrachlorodibenzo-p-dioxin -TCDD-, polychlorinated dibenzofurans -PCDF-);
- Nonylphenol;
- Per- and polyfluoroalkyl substances (PFAs, among which Perfluorooctanoic acid -PFOA- and Perfluorooctane sulfonate -PFOS-);
- Cadmium and Polycyclic aromatic hydrocarbons (PAH16), with lower priority.

The risk assessment regards also food waste, which is a category of waste which can be digested anaerobically and give so a digestate which can be used for agricultural purposes. While most concerns are focused on sewage sludge application on soil, food waste digestate should not have a relevant impact. The information provided in [2] is confirmed also by a JRC report on "End-of-waste criteria for biodegradable waste subjected to biological treatment (compost & digestate): Technical proposals" [3].

For what has been above said it is interesting to evaluate the impact of the agronomic use of digestate. The objective of this work is to use the data collected during the irexfo LIFE16 project on food waste prevention and valorization, to perform a LCA study on the impact of food waste digestate agronomic use. In fact, this is not possible at the moment in Italy, because of the Decree of the 25th February 2016 [4] on the disposal of digestate produced from raw materials, which are not considered biomasses. In the EU Regulation of 2019/1009 [5] of the European Parliament and of the council of the 5th of June 2019, some Component Materials Categories (CMCs) are identified, which can be considered as fertilizers; among them "digestate other than fresh crop digestate" includes digestate produced from bio-waste for example; another category takes into consideration food industry wastes. This work is inserted so also in the framework of the end of waste discussion.

The paper is organized in the following way: after presenting the materials and methods section, in which all the assumptions relative to the LCA study are reported; the results will be proposed, in which the flows of heavy metals will be illustrated and the final results of the impacts in different categories will be presented; in the discussion section the results will be compered with current literature and further developments with be also identified.

2 Materials and methods

2.1 Digestate characterization

To understand the impact of digestate (see figure 1) disposal a key aspect is its composition, especially in terms of polluting substances.

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Fig. 1. Digestate from a plant situated in Umbria region

The characterization of the digestate is presented in table 1 [6]. To have reliable data on the content of heavy metals we have considered the analysis reported in [7]. In this work in fact the composition of digestate has been carefully analyzed, including organic matter content and plant-available nutrients concentrations, as well as possibly harmful properties, e.g. heavy metals and pathogens. Five samples of digestate have been analyzed: 3 digestate from food waste, 1 digestate from the organic fraction of municipal wastes and 1 digestate from a mixture of waste vegetable and activated sludge, the results of the analysis of food waste digestate are presented in table 2. Data on feedstock, digestate and heavy metal load in the field are the average of 3 samples.

Table 1. Digestate characterization.

Paramter	**Value**	**Unit**
Ash	12.38	wt% d.b.
Volatile Matter	67.07	wt% d.b.
Fixed Carbon	20.55	wt% d.b.
VM/FC	3.29	wt% d.b.
C	42.52	wt% d.b.
H	5.94	wt% d.b.
N	1.79	wt% d.b.
O	49.75	wt% d.b.
Cellulose	21.64	wt% d.b.
Hemicellulose	15.08	wt% d.b.
Lignin	40.88	wt% d.b.
Extractives	10.02	wt% d.b.
Higher Heating Value	19.74	MJ/kg d.b.
*d.b. stays for dry basis		

Table 2. Heavy metals concentration in digestate and substrate [7]

Heavy Metals	Feedstock (mg/kgTS)	Digestate (mg/kgTS)	Regulatory limit -EU proposal [8] (mg/kgTS)	Heavy metal load in the field* (g/ha/year)
Pb	1.03	4.43	120	5.5
Ni	0.7	25.6	50	27.7
Hg	0.07	0.13	1	0.2
Cd	0.06	0.2	1.5	0.2
As	0.47	0.7	NA	0.8
Cu	6.33	23.23	200	29.4
Cr	2.07	9.73	100	147.9
Zn	31.8	128.53	600	13.0

* Digestate spreading calculated according to [7] based on TKN rate of 170 kgTKN/ha.

Dealing with the concentration of heavy metals and polluting substances, according to the literature [9], there is no apparent difference between digestate and compost. So considering that the heavy metals don't undergo to changes during the composting or anaerobic digestion processes, it depends only on how much organic matter (or volatiles) are converted during the process and also the final humidity of the material, these two parameters give an idea of how much "diluted" will be the heavy metals, by the content of organic matter and water.

2.2 Goal and Scope and LCI analysis

Considering the high interest on waste food reduction derived from the Sustainable Development Goals (SDG) of the United Nations and in particular the SDG 12.3, in these late years the studies on food waste reduction have definitely increased, see [10,11] as examples. On the other hand, no study has analyzed the behavior of heavy metals.
For this reason, the goal of this work is to compare the environmental impact of two possible scenarios:
1. application of the digestate directly on the fields;
2. composting of the digestate and then application on the fields.
The boundaries of the LCA in both the considered scenarios are shown in figure 2. The study is based on ISO 14040 and ISO 14044. Given that the anaerobic digestion plant simulation has been already realized and discussed in other papers, see [12] and that the digestate complete characterization is provided in tables 1 and 2, the remaining part of the analysis is focused on:
- the composting process (see figure 2);
- the behavior of heavy metals in the soil and water;
- The behavior of N and P in the soil and water.

The storage of the digested is neglected and so the emissions which are generated in this phase.
The analysis is performed based on the following functional unit: treatment of food waste; and reference flow: 1 ton of treated food waste.
The composting process can be easily modelled referring to the process "Biowaste {CH}| treatment of biowaste, industrial composting| Cut-off, S", taken from the database Ecoinvent 3.4. The process has three main inputs: electricity, the compositing infrastructure and the diesel fuel; while as output the emissions released in the air are considered. Another interesting aspect to be taken into consideration is the change of organic and mineral matter during the compositing process. For what concerns the changes in organic matter, we see

that the composting process increases the polypeptide content, probably due to an increase in the microbial population and the composting yields a more stable and humified organic matter, which is richer in aromatic structures. In general composts show a lower labile organic matter fraction than the starting sludges, and consequently lower microbial activity [13]. Dealing with the nutrients behavior during composting, the only one which is influenced in an important way is nitrogen. In fact, the nitrogen which is present in the digestate tends to pass in form of ammonia in the gaseous phase, during the treatment [14]. The loss of nitrogen during the aerobic treatment or composting is estimated to be about 13.13%. Then it has also to be evaluated the difference between the emissions of CO_2 and N_2O in air, due to the degradation of the digestate or the compost, once they are applied in the soil. Dealing with the CO_2 emissions, these are biogenic and are equal to 86-96% of the total carbon content. On the other hand N_2O-N emissions are equal to 1.3-1.7% of the total applied nitrogen [15].

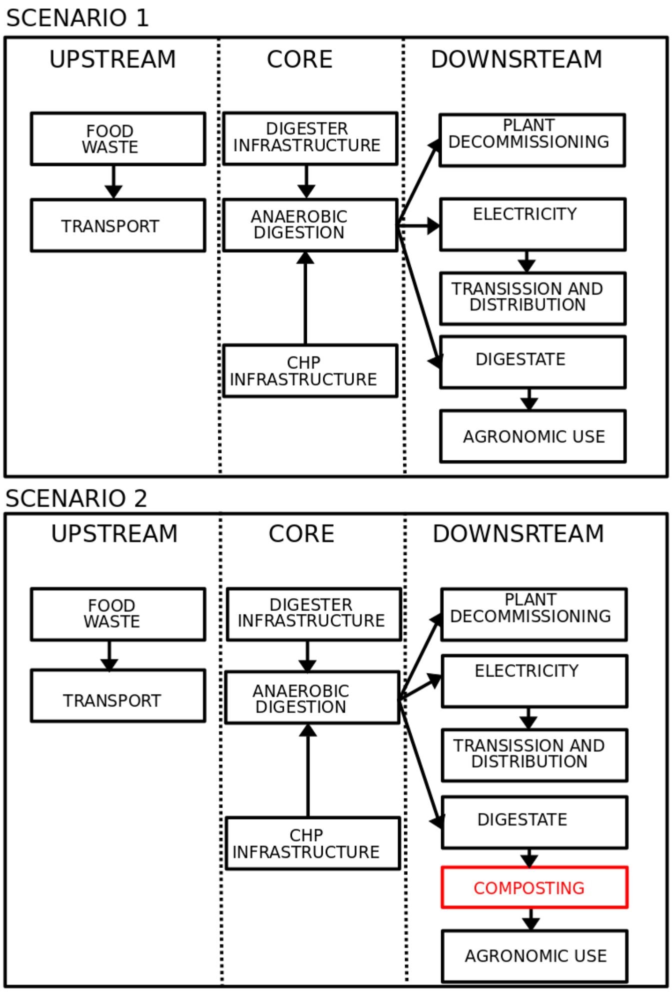

Fig. 2. LCA system boundaries for the two scenarios considered

Dealing with the behavior of nutrients (in particular N and P) in the soil, this can also be modelled referring to the Product Category Rule (PCR) “Arable crops” version 2.0, taken from the Environdec system [16]. In this we find that the emissions in air and water of the nutrients can be calculated according to the methods reported in Table 3.

Table 3. Emissions coefficients calculation procedures [16]

	Emission	**Source**
Emission in air	Ammonia	[17]
	N_2O, NO-direct emission	[18]
	N_2O-indirect emission	[19]
Emission in Water	Nitrates	[19]
	Phosphorus	[20]

The conversion coefficient indicated in the Chapter 11 of the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories [21] to pass from N_2O-N to N_2O is equal to 44/28, so the conversion equation results to be:

$$N_2O = N_2O\text{-}N*44/28 \tag{1}$$

Having an emission coefficient for nitrogen oxides (1.3-1.7 wt%), which is proportional to the quantity of nitrogen contained in the compost and digestate, this means that we can assume that the emissions are only proportional to the nitrogen content of the digestate and of the compost. The compost during the process will lose part of the nitrogen content, as above reported. Dealing with the analysis of the heavy metals behavior and their partitioning, once that the digestate or compost are applied to the soil, we can assume to use the equations reported in the SALCA (Swiss Agricultural Life Cycle Assessment) [22]. In particular we employed the method SALCA Heavy Metals, a method for recording heavy-metal flows, taking account of the following elements: Cd, Co, Zn, Pb, Ni, Cr and Hg. Emissions into agricultural soil, into surface waters and into groundwater are determined taking into account the heavy-metal input from seeds, fertilizers, plant-protection products and feedstuffs, as well as the deposition. An allocation factor is used to distinguish between diffuse inputs and those caused by agriculture. The method makes use of generic coefficients which are valid for Switzerland, but can be translated also to the Italian situation. For what concerns the leaching into groundwaters or superficial waters, it can be reasonably assumed that ground waters are not interested by the leaching, while the surface waters will. The equation to calculate superficial waters runoff is the following:

$$L\_m\_i = L\_a\_i * A\_i \tag{2}$$

Where L_m_i is the mass of leached metal, L_a_i is the average leaching rate (see Table 4) and A_i is the allocation factor. The Allocation finds its reason because part of the heavy metals, which are located in the soil are coming also from the atmospheric deposition. This contribution should be subtracted to the total, so that only the heavy metals added with the digestate and compost is taken into account. The allocation factor contains in the denominator the sum of the quantity apported by the digestate/compost and the quantity derived from atmospheric deposition.

$$A\_i = m\_agr/(m\_agr + m\_dep) \tag{3}$$

Where A_i is the allocation factor of heavy metal i, m_agr is the mass of heavy metal applied in the soil (which is reported in table 2, the last column) and m_dep is the mass of heavy metal deposited from the atmosphere, which is reported in table 5.

Table 4. Leaching rate of heavy metals [23]

	Cd	Cu	Zn	Pb	Ni	Cr	Hg
L_a_i (mg/ha)	50	3600	33000	600	n.a.	21200	1.3

Table 5. Emissions coefficients

	Cd	Cu	Zn	Pb	Ni	Cr	Hg
m_dep (g/(ha*year))	0.7	2.4	90.4	18.7	5.475	3.65	0.05

The erosion process is modelled, using the following equation:

$$M\_er\_i = HM\_ci * B * a * f_{Erosion} * A\_i \quad (4)$$

Where M_er_i is the mass of heavy metal, which is interested by erosion (g/ha*year), HM_ci (mg/kg) is the concentration of heavy metal i in the field, B is the annual erosion rate reported in [26] and equal to 4 t/ha*year, a is another constant factor which is influenced by the quality of the soil and it is assumed equal to 1.86, Ai is the allocation factor, $f_{Erosion}$ is a constant coefficient that estimate how much of the eroded heavy metal will reach the water (it is estimated to be 0.2). The HM_ci is a constant which is different for different soils and it is reported in table 6.

Table 6. Concentration of heavy metals in the soil [22]

	Cd	Cu	Zn	Pb	Ni	Cr	Hg
HM_ci (mg/kg)	0.307	39.2	70.1	24.9	24.8	27.0	0.077

Once the leaching and the erosion phenomena have been calculated they are summed and considered as emissions to water. The remaining quantity obtained subtracting the emissions to water from the total, is considered as soil emissions. The metals shown in table 2 are 8, while those shown in tables 3,4,5 are 7. The As is not comprised in the tables so it is assumed it behaves like Cr. Concerning the LCIA method used in this analysis:

- the project was implemented in the software OpenLCA version 1.10.2. This is an open source software for performing LCA analysis. It is developed by Green Delta GmbH. The user needs to buy obviously LCA databases, which are not free (eg. Ecoinvent, Agrifootprint and others);

- the impact evaluation method used was the CML baseline method, which is named after the Institute which developed it, the Institute of Environmental Sciences of the Leiden University. This is one of the oldest and most used impact assessment method, in which we find midpoint impact categories but not endpoint impact categories [11].

3 Results

The chord diagram simulating heavy metals partitioning in the two phases of the environment (soil and water) is shown in figure 3 and has been realized with the open source software Circos [27].
Chord diagrams are very useful to study interconnected areas in an LCA or to perform and visualize the so-called NEXUSES (eg. energy-water; food-energy and food-water nexuses). Here the diagram is used to clearly display the interactions between two spheres of the environment: water and soil. We can see from the graph for example that copper is highly leachable and passes to water very easily. The same is for the great part of nickel, released into the soil both by air deposition and by the agronomic inputs. The partitioning between soil and water is expressed as percentage of the total input, which is derived from the sum of the air deposition and the agronomic inputs.
The final impact of the application of the digestate and of the compost in the soil is proposed in table 7. From here we can see that the composting process of the digestate, when following the anaerobic digestion does not correspond to environmental advantages, in fact the impact on the ecosystem, which is mainly due to the effect of heavy metals remains almost the same, while the impact on the Climate Change category is greatly increased, due to the use of electricity and heat during the composting process. The emissions from the compositing process are not balanced by the benefits obtained when the compost is applied in the soil. In fact, we have only a small reduction of the production of nitrous oxides and ammonia.

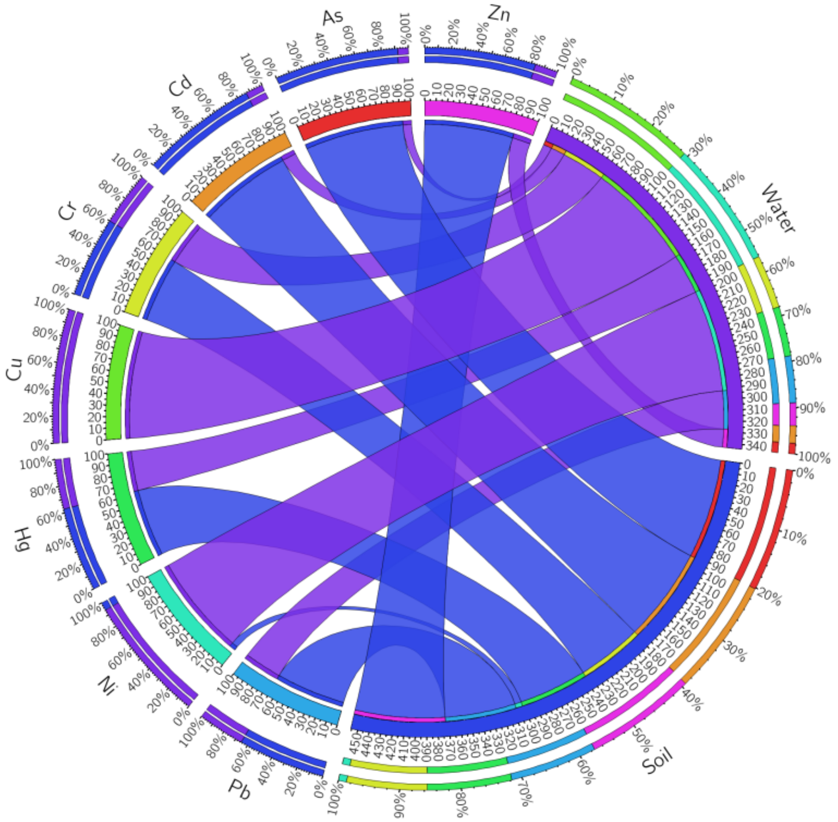

Fig. 3. Chord diagram about the partitioning of heavy metals in water and soil.

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Table 7. Final Results of the LCA analysis.

Impact category	Digestate	Compost	Unit
Freshwater aquatic ecotoxicity	6.47E+01	7.03E+01	kg 1,4-dichlorobenzene eq.
Marine aquatic ecotoxicity	5.80E+04	7.26E+04	kg 1,4-dichlorobenzene eq.
Ozone layer depletion	4.31E-06	7.69E-06	kg CFC-11 eq.
Human toxicity	4.05E+02	4.14E+02	kg 1,4-dichlorobenzene eq.
Photochemical oxidation	4.44E-02	5.42E-02	kg ethylene eq.
Eutrophication	8.83E-01	1.11E+00	kg PO4--- eq.
Acidification potential	2.14E+00	3.17E+00	kg SO2 eq.
Climate change - GWP100	7.22E+01	3.36E+02	kg CO_2 eq.
Terrestrial ecotoxicity	2.16E+02	2.16E+02	kg 1,4-dichlorobenzene eq.
Depletion of abiotic resources	4.04E+02	6.50E+02	MJ
Depletion of abiotic resources	2.00E-04	2.50E-04	kg antimony eq.
Freshwater aquatic ecotoxicity	6.47E+01	7.03E+01	kg 1,4-dichlorobenzene eq.

In figure 4 it is presented the contribution of each process of the life cycle to the impact on the categories involving the Ecotoxicity and Human Toxicity: Freshwater Ecotoxicity, Marine Ecotoxicity, Human Toxicity and Terrestrial Ecotoxicity.

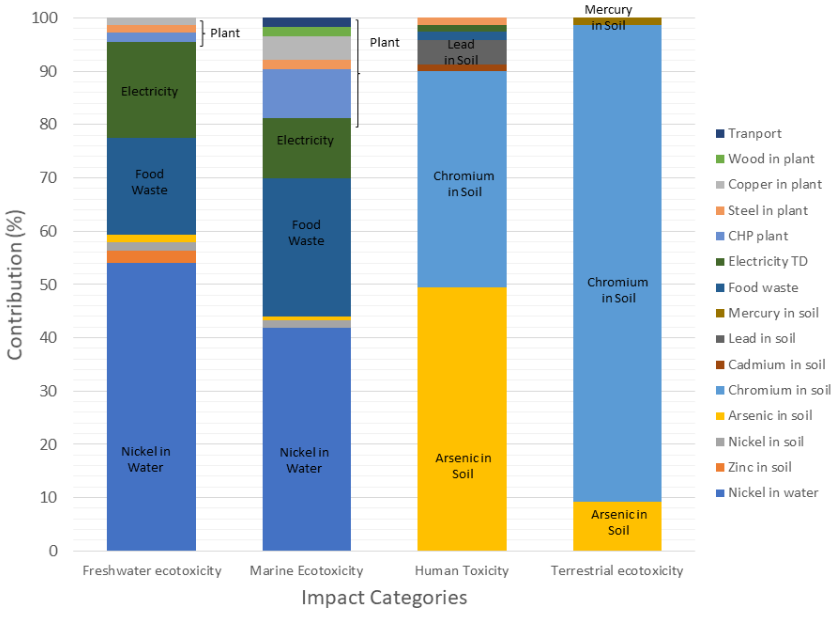

Fig. 4. Contribution of the single life cycle phases to the total impact in the categories dealing with Ecotoxicity and Human Toxicity – SCENARIO 1

We can see from figure 4 that nickel in water contributes for more than 50% to the impact category on Freshwater Ecotoxicity and for more than 40% to the impact category on Marine Ecotoxicity. Arsenic in the soil contributes to about 50% of the impact on Human Toxicity and 10% of the impact on Terrestrial Ecotoxicity. Chromium in the soil contributes to about 40% of the total impact on Human Toxicity and more than 90% of the impact on Terrestrial Ecotoxicity. The emissions of zinc in soil and nickel in the soil have reduced contributions to all the impacts on toxicity. The process "Food Waste" indicates the impact of the logistic chains which are necessary to supply the food waste to the anaerobic digestion plant and to treat it, separating it from packaging and other materials which will be discarded. The process of food waste collection and pretreatment contributes to more than 15% of the impact on Freshwater Toxicity and more than 25% of the impact on Marine Toxicity. The electricity process is used mainly for the pretreatment of the food waste and also to cover the auto-consumption of the biogas plant. Electricity production contributes to more than 10% of the impact in the category Freshwater Ecotoxicity and to 10% of the impact in Marine Toxicity. The materials of which the biogas plant is made (mainly concrete, steel, wood, plastics) contribute for less than 5% to the category Freshwater Ecotoxicity and about 20% of the impact in Marine Toxicity.
In figure 5 the remaining impact categories are presented, in these categories we see that other processes are involved. This means that heavy metals, obviously, contribute only to the impact on ecosystem and human toxicity.
We see from figure 5 that the logistics and pretreatment of food waste contributes to more than 50% of the impact in the categories: Ozone Depletion, Photochemical Oxidation, Climate Change and Fossil Resources.

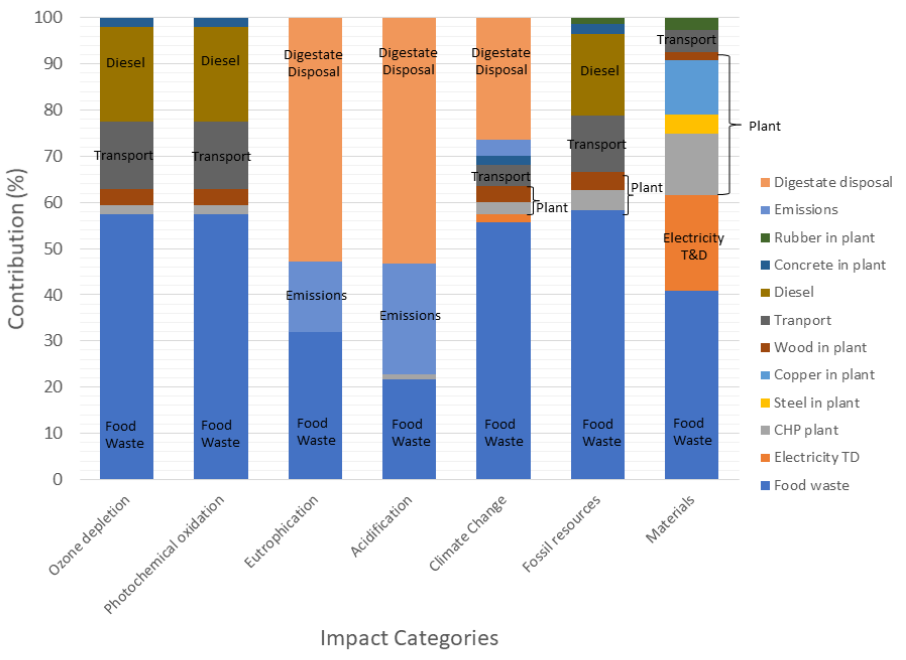

Fig. 5. Contribution of the single life cycle phases to the total impacts in the categories: ozone depletion, photochemical oxidation, eutrophication, acidification, climate change, fossil resources and materials consumption – SCENARIO 1

In the category materials the contribution of the process food waste is higher than 40%. The process transport represents the transport of the other auxiliary materials used in the life cycle of food waste treatment. This accounts for about 10% of the impact in the categories: Ozone Depletion, Photochemical Oxidation and Fossil Resources. The diesel production process accounts also for more than 10% of the impact in the same categories. The digestate disposal process mainly represents the use of the digestate as fertilizer in the soil. This produces emissions in the air due to nitrogen degradation and also leaching of nitrates and phosphates, which contribute to Acidification and Eutrophication. For this reason, the process digestate disposal contributes for more than 50% to the impact categories Acidification and Eutrophication. Dealing with the impact category Climate Change, the digestate disposal process contributes for more than 20% of its impact, due to the emissions from the soil of nitrogen oxides.

Given that the second scenario has more or less the same impact on the toxicity categories we propose in figure 6 a comparison between the contribution of the processes in the category where the difference between the two considered scenarios is bigger, that is: Climate Change.

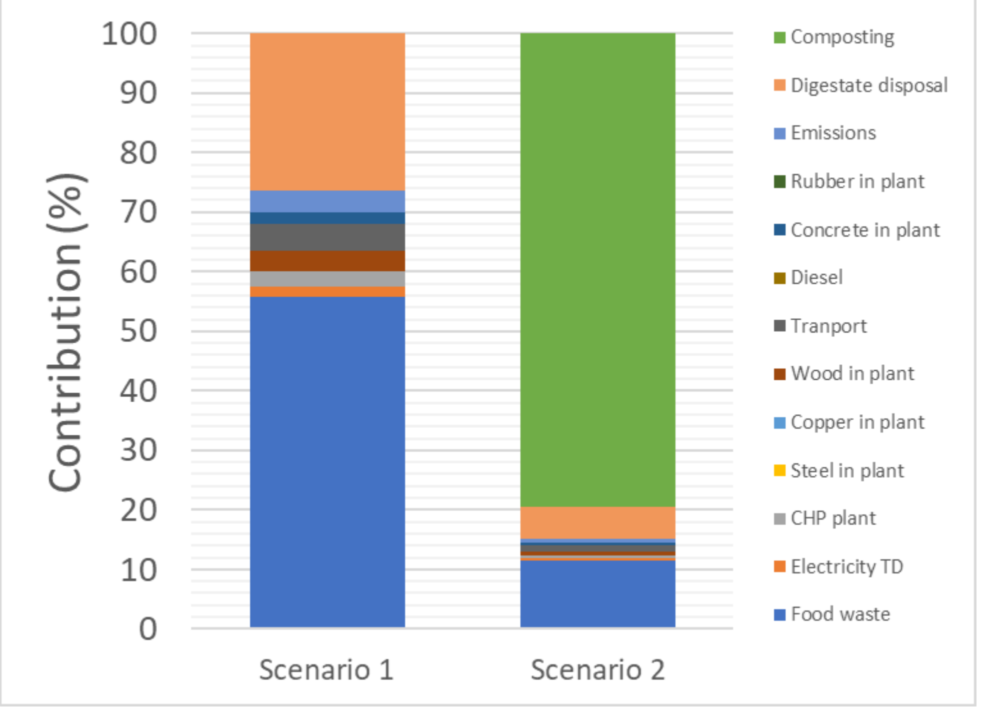

Fig. 6. Comparison between the process contributions to the impact category Climate Change between the SCENARIO 1 and SCENARIO 2

As it can be seen from figure 6 in the scenario 2 more than 80% of the impact on Climate Change is produced by the composting process which anaerobically stabilizes the digestate, but consumes also electricity and emits CO2. The release of GHG emissions can be reduced by applying the digestate directly into the soil.

4 Discussion

If we compare the results of this study with those shown in [11] we can see that the impact on Climate Change is not so different. In this study it is calculated to be equal to 72.2 kgCO_2/t of food waste, while in [11] is estimated to be about 96.97 kgCO_2/t of food waste. The big differences between the two studies are the following:

- in [11] the impact of food waste collection and transport are not considered;
- in [11] the digestate of the anaerobic digestion plant is not used for agronomic purposes, so as a fertilizer, but it is centrifuged and the solid part is used in an incineration plant and so disposed of; while the liquid part is disposed with a wastewater treatment and deodorization.

This means that the scenario 1 in our case has lower impact on Climate Change but high impact on human and environmental toxicity; due to the effect of heavy metals. This effect is not reduced by the composting process which has even a higher impact on Climate Change category.

The results of the study are also confirmed by the study of Mondello et al. 2017 [28], which report very similar values for acidification, eutrophication and climate change. In the study of Mondello et al. [28] four scenarios are compared: landfill, incineration, composting, biogas and insects production with the food waste, to obtain proteins. Of all the compared scenarios biogas confirms to be the more convenient at least in the Climate change category.

So our study indicates that if the legal thresholds for the concentration of heavy metals in the digestate are always met, the agronomic use is feasible by a legal point of view and it is also economic and environmentally sustainable. Maybe some leaching experiments can be conducted to study how much heavy metals can be recovered from this substrate (both liquid and solid phases obtained after phase separation).

Another option can be the use of digestate (at least the solid part separated from the liquid with a press) in the pyrolysis process. By coupling anaerobic digestion and pyrolysis we can obtain many advantages, like: the production of a more stable soil amendment like biochar and also the production of energy vectors like the oils and the pyrolysis gas. In this sense the University of Perugia (in particular the Biomass Research Center) has already participated to a BRISK2 project on catalytic pyrolysis of digestate using mainly Y zeolites and iron to produce upgraded pyrolysis liquids. So this represents a future development for the research.

5 Conclusions

Starting from the necessity to reduce the production of food waste, the study has taken into consideration two different scenarios, to perform the anaerobic digestion of food waste and then use directly the digestate produced as soil amendment for agronomic purposes, or to use the digestate after a further step of aerobic treatment (compositing). The first scenario has similar performance on the impact on the toxicity on environment and human toxicity. This is due to the fact that the heavy metals concentrations, calculated through the SALCA (Swiss Agricultural Life Cycle Assessment), are not affected by the two processes. A significant difference between the two analysed scenarios is detected instead in the impact category of Climate Change, in fact the composting process has a high contribution to GHG emissions. Particular attention has been directed to the partitioning of heavy metals in water and soil. The final concentration of heavy metals contained in the digestate of food waste (composted and not composted) is far below the legal limits, nevertheless it has an undeniable impact. Nickel when emitted in the water contributes for more than 50% to the impact category on Freshwater Ecotoxicity and for more than 40% to the impact category on Marine Ecotoxicity. Arsenic when emitted in the soil contributes to about 50% of the impact on Human Toxicity and 10% of the impact on Terrestrial Ecotoxicity. Chromium in the soil contributes to about 40% of the total impact on Human toxicity and more than 90% of the impact on terrestrial ecotoxicity. The emissions of zinc in soil and nickel in the soil have reduced contributions to all the impacts on toxicity. To reduce this problem a possible solution can be represented by a thermochemical treatment through pyrolysis. The thermochemical processes could be the optimal way to treat the digestate, instead of composting it. Through a thermochemical treatment at temperatures which are higher than 400°C mercury would be eliminated in the flue gases and the other heavy metals could be more stabilized and retained in the solid char. In the case of thermochemical processes the final product which will be obtained from waste food digestate would be a biochar. This can be leached with special techniques to separate the contained heavy metals; obtaining a completely clean sub product and recycling also in this way the heavy metals. These techniques have been already experimented for the charcoal obtained from sewage sludge, for example, see [29].

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