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Life Cycle Assessment of pelletized compost from agricultural waste valorization processes

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Abstract

In the context of agricultural waste management, the production of compost to fertilize the soil is a practice that presents benefits from both a technical-economic and an environmental point of view. However, the use of compost shows relevant issues related to storage, handling, and relocation. Pelletization is a promising technique to overcome such problems: thanks to low water content the pelletized compost avoids the formation of mold and possible contamination by pathogenic microorganisms, as well as the development of bad odor. Along with the reduction in volume, these aspects make long-distance transport and storage possible, whereas untreated compost is preferably used in the same place where it is produced. In the present study, the Life Cycle Assessment (LCA) was carried out to evaluate the benefits given by the pelletizing treatment of compost obtained from leafy agro-waste compared to the direct use of the compost on-site. The fertilizing value has been taken as the functional unit (FU), instead of a mass-based FU, and the results showed better environmental performance of the pellet over the compost. Energy consumption optimization scenarios were also evaluated through a sensitivity analysis, which showed the possibility to further improve the environmental results of the pellets.

Keywords: agricultural biowaste; compost pellets; fertilizing value; Life Cycle Assessment

1. Introduction

The problem of valorizing food losses and waste is of crucial importance since, according to the Food and Agriculture Organization of the United States (FAO), one third of the food produced globally is wasted along the food value chain (FAO, 2011). A report of the World Wide Fund for Nature (WWF) on food waste in primary production highlights that the food waste generated during harvesting phase accounts for the 28.5% of the total food waste produced in the United Kingdom in 2021 (WWF-UK, 2022). At the harvesting stage, food is considered as waste when it is sent to one of the following destinations: composting, anaerobic digestion, landfill or incineration. Moreover, in the same WWF report it is stressed that fruit and vegetables, being very perishable products, represent the first source of waste and losses. In particular, from 40% to 50% of their production is discarded (Cassani and Gomez-Zavaglia, 2022). Despite the large quantities of agri-food waste produced, their contribution in terms of carbon footprint remains limited, accounting for around the 7% of the total greenhouse gases emissions of waste from primary production (WWF-UK, 2022). Among agricultural waste management practices, composting is one of the most common (Ronga et al., 2020). Compost is a mixture of substances generated by bio-oxidation and humification, operated by of macro and microorganisms, of plant or animal biodegradable organic materials. In addition to the function of ensuring circularity, the use of compost has important advantages on the soil itself: it improves the characteristics and structure of the soil, and it increases soil productivity thanks to its fertilizing value. Furthermore, compost acts as a biological activator with positive effects on biodiversity (Liu et al., 2016). These numerous advantages, however, are accompanied by various issues related to compost management. The first issue concerns its high-water content, which reduces delocalization (Sarlaki et al., 2020): the higher the moisture content, the greater the volumes to be handled. Furthermore, compost is difficult to store, because of its tendency to cause unpleasant odors and to form mold (Ayilara et al., 2020). For these two reasons, compost is mostly used near the production site, and it is commercially disadvantaged compared to chemical fertilizers.

From a production point of view there are two ways to produce compost: aerobically via decomposition of organic residues, or anaerobically as a by-product of biogas. This by-product is commonly called digestate.

The compost obtained from the decomposition of organic residues can be commercialized in three formats: in bulk, packaged in bags or pelletized. The packaged compost is easier to store and distribute, but it does not eliminate the problems of mold and odors. At the same time, however, there are higher costs for packaging and a higher risk of breaking the bags during their handling. Pelletized compost is the best solution from a handling and storage point of view. Pelletizing consists in the extrusion of compost through holes, in order to obtain cylindrical structures of variable length, called pellet. Inside the pellet there is a high concentration of nutrients thanks to the decrease in humidity, which stands at around 7%. Compost humidity, on the contrary, is around 30% (Ronga et al., 2020). At the same time, thanks to the pressure and temperature at which the pelletization is carried out, it is possible to eliminate harmful microorganisms and molds. The reduction in pH (Lo´pez-Mosquera et al., 2008) makes the product safe from bacterial proliferation and suitable for long storage.

2. State of the art

At the scientific literature level, the problem of valorizing waste from the agri-food sector is widely covered. However, there are few studies documenting the potential environmental benefits of producing pellets from compost. A literature review was carried out on the Scopus database by setting the search of specific keywords within the title, abstract and keywords. The combination of keywords "Life Cycle Assessment" AND (pellet OR pelletizing) AND (fertilizing OR compost) produced the highest number results (32). The paper selection was carried out by analyzing the title and the abstract and only two studies were considered in line with the search criteria.

Li et al. quantified the environmental impact of wheat straw pellets production. 1 kg of pellet was used as the functional unit (FU) and the results showed that drying and pelletizing processes gave the highest contribution to the environmental burdens (Li et al., 2012). A mass-based FU was also chosen by Sarlaki et al. in the comparison between pelletized-dried compost and untreated compost. It was found that, despite the increase in the energy consumption related to pelletizing-drying, the pelletized-dried compost has a superior environmental performance in terms of the human health, climate change, and ecosystem quality damage (Sarlaki et al., 2021).

The lack of studies that take the fertilizing value of the compost as the function of the system, to be placed at the center of the environmental analysis, represents the major contribution of the present study.

3. Materials and Methods

The LCA methodology was applied according to the reference standards ISO 14040 and 14044 and the SimaPro software 9.3 with Ecoinvent 3.8 was used to carry out the analysis. The first phase of the methodology is the goal and scope definition, which includes the definition of the functional unit (FU) and the system boundaries. The FU quantifies the functional performance of the system, and it is the quantity to which the input data and the results should be referred to, in order to guarantee, especially in comparative analyses, that the two alternative systems cover the same function. In the present study the fertilizing value was chosen as the FU instead of a mass-based FU. The system boundaries define the geographical, temporal, and physical references of the study. In particular, the physical boundaries set the type of analysis according to the life cycle stages included. The present study covers all the life cycle stages from the recovery of agricultural waste, used as raw material, till the compost distribution phase and, therefore, it outlines a “from cradle to grave” pathway. In the analysis all the input-output flows have been collected and processed to refer them to the functional unit. Moreover, each single type of consumption was modelled in the SimaPro software using the Ecoinvent datasets, which represent unitary process with known emission values. The modeling was carried out according to the rules of the Cut-off approach. For this reason, the agricultural waste, from which the compost is produced, was attributed zero impact. The composition of the waste is still a relevant parameter because it determines the fertilizing value of the compost.

The assembly of the different datasets allows the construction of a complex system and an emissions inventory which represents the starting point of the subsequent impact assessment. The quantification of the impact results was performed using the EPD (2018) method, which includes the following seven impact categories: acidification potential (kg SO_2 eq), eutrophication potential (kg PO_4^{---} eq), global warming potential (kg CO_2 eq), photochemical oxidation (kg NMVOC), abiotic depletion of elements (kg Sb eq) and fossil fuels (MJ), water scarcity (m^3), ozone layer depletion potential (kg CFC-11 eq). Eutrophication, global warming, ozone depletion and abiotic resource depletion are taken from the CML-IA baseline method. Water scarcity category is based on AWARE method and Photochemical oxidation is based on ReCiPe 2008. The characterization factors related to global warming potential are updated to the IPCC 5th Assessment Report (AR5), which dates back to 2013.

In the interpretation of the results, the main hotspots were identified, and possible improvement scenarios were evaluated through a sensitivity analysis.

3.1. Goal and scope definition

The objective of the study is to identify the potential benefits of using pellets for fertilizer use as an alternative to compost which presents significant storage and delocalization problems. In line with the goal of the study, the fertilizing value, represented by the carbon content, was chosen as the FU. In absence of primary data on additional nutrients, such as phosphorus and potassium, it was preferred to consider carbon alone in the definition of the fertilizing value, rather than a combination of nutrients. As far as the system boundaries are concerned, the phases included in the analysis are represented in Figure 1. The geographical reference is that of the Salerno area where the agricultural consortium that provided the primary data is located. Temporally the data refers to the year 2023.

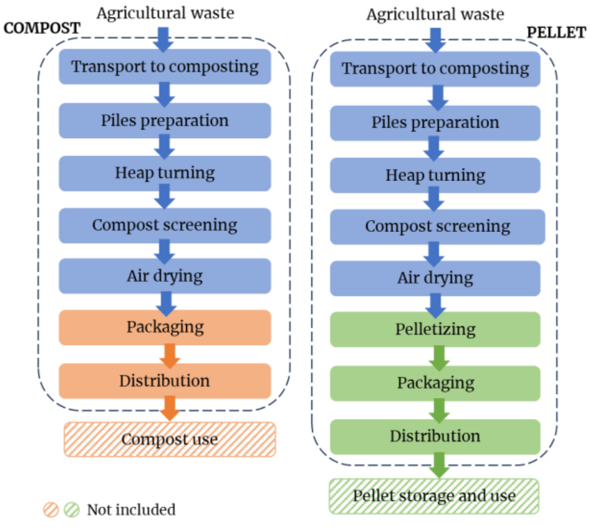

Figure 1. System boundaries

3.2. Inventory analysis

In the inventory analysis consumption data relating to the phases detailed in Figure 1 were collected. The composting plant can produce 35,000 tons/year of compost from the agricultural waste generated by the consortium itself. The waste from which the compost under study was produced is composed of 35% radicchio, 25% endive, 10% spinach and 20% olive tree pruning. In the case of the pelletized product, the process consists of eight main phases, namely the transport to the composting site, preparation of the piles using a mechanical shovel, heaps turning, compost screening, air drying, pelletization, product packaging and distribution to customers. In the case of untreated compost, drying and pelletization are not carried out. the consumption data associated with each phase are shown in Table 1. The consumption of the machinery was obtained starting from the available information related to the power and productivity of the machine and to the quantity of material treated. It was assumed that the turning machines were diesel powered and, therefore, the Ecoinvent dataset *Diesel, burned in agricultural machinery {GLO}* was used. The screening machine, the pelletizer and packaging machine instead run on electricity (*Electricity, low voltage {IT}*). For the packaging phase it was assumed that 10 kg bags and a packaging machine with a power of 10 kW and a productivity of 720 bags/h are used. As regards the distribution phase an average distance of 100 km travelled with a Euro 5 truck (*Transport, freight, lorry 16-32 metric ton, EURO 5 {RER}*) was assumed. As regards the transport to the composting site, the distance travelled with a Euro 3 truck could be neglected, as it is about 300 m, but it was considered anyway. Such consumption was represented with the dataset *Transport, freight, lorry 3.5-7.5 metric ton, EURO 3 {RER}*. From a methodological point of view, 1 kg of each product was firstly modelled and subsequently the values were scaled for the respective mass quantities produced to fulfill the specific function. In particular, a carbon content of 365 g was set, which is equal to the quantity contained in 1 kg of pellets. 1.3 kg of compost is needed to achieve the same fertilizing value.

Table 1. Input and ouput flows referred to the FU

Life cycle stage	Type of consumption	Quantity per kg pellet	Quantity per 1,3 kg compost
Piles preparation	Energy from diesel combustion	0.6705 MJ	0.7470 MJ
Heaps turning	Energy from diesel combustion	0.2703 MJ	0.2995 MJ
Compost screening	Electricity	0.0039 kWh	0.0043 MJ
Pelletization	Electricity	0.0462 kWh	-
Packaging	Electricity	0.0014 kWh	0.0018 kWh

4. Results and Discussion

The environmental results show that pellet is the system with the lowest environmental impact in most of the impact categories. However, the difference between the results of the two systems is minimal, as shown in Figure 2. In particular, the environmental savings related the global warming potential (GWP) category represent only 1%. It must be underlined that the environmental results do not include the benefits given by the possibility of storing the product for a longer time and transport it over long distances, because only the phases for which the two systems can actually be compared were considered. The fact that the additional pelletizing step does not lead to an increase in the environmental impact, except for three impact categories (abiotic depletion of element, water scarcity and ozone layer depletion) makes the advantages of using pellets exploitable without causing environmental damage.

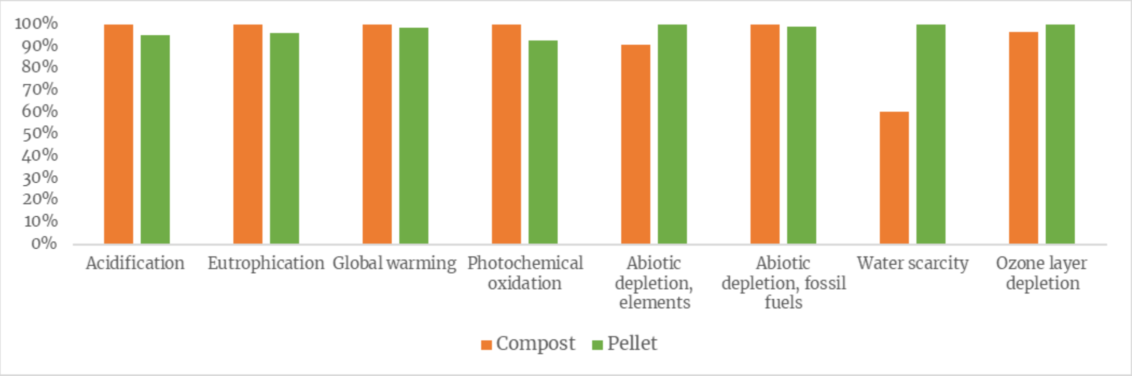

Figure 2. Percentage comparison of the environmental results

The numerical values of the impacts are reported in Table 2.

Table 2. Environmental resuls

Impact category	Unit	Compost	Pellet
Acidification	kg SO_2 eq	1.08E-03	9.86E-04
Eutrophication	kg PO_4^{---} eq	2.48E-04	2.31E-04
Global warming	kg CO_2 eq	1.69E-01	1.52E-01
Photochemical oxidation	kg NMVOC	1.53E-03	1.38E-03
Abiotic depletion, elements	kg Sb eq	9.66E-07	1.10E-06
Abiotic depletion, fossil fuels	MJ	2.11E+00	1.90E+00
Water scarcity	m^3 eq	1.42E-02	1.60E-02
Ozone layer depletion	kg CFC-11 eq	2.28E-09	2.25E-09

The additional consumption of electricity introduced by pelletization has negative consequences on water scarcity, resulting in a difference of approximately 40% between the results of the two products. In order to study the possible improvement scenarios, it is useful to identify which processes contribute the most to the total environmental impact. Figure 3 focuses on GWP and shows that the highest contribution is that of piles preparation (54%), followed by the turning of the piles (21%). The pelletization phase accounts for the 11% of the GWP impact and it is the pelletizing process, being the only one not in common with the compost system, that should be optimized. For this reason, a sensitivity analysis on the pelletization phase has been performed.

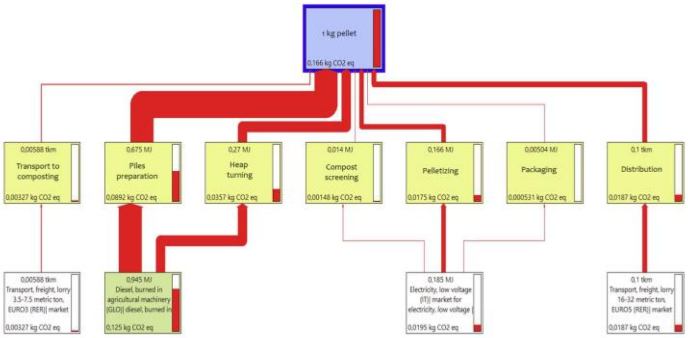

Figure 3. Tree diagram related to 1 kg of pellet and GWP contribution of the life cycle stages

4.1. Sensitivity analysis

The sensitivity analysis has the aim of evaluating the changes in the results occurring as a consequence of the variation in the input parameters. In particular, for the purpose of identifying the best strategy to reduce the environmental impact of the pelletized compost, an optimization of the energy consumption must be performed. Although the most impactful phase is the piles preparation, the phase of highest interest for this study is the pelletization phase, being the additional phase compared to compost production. It was assumed that the electricity consumed by the pelletizing machine could be the renewable energy generated by photovoltaic panels, according to similar studies in the food sector (Paini et al., 2023). The Ecoinvent dataset chosen to represent such energy source is *Electricity, low voltage {IT}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | Cut-off, S.* The use of renewable energy allows a reduction of the environmental impact in all the impact categories except for the abiotic deletion of elements, as shown in Figure 4. The reduction is of 81% for the GWP and of 68% for the water scarcity. Considering the effect of the change in the pelletizing phase on the total environmental results of pelletized compost, compared to untreated compost, it can be noted that further improvements in the environmental performance of the pelletized compost are achieved.

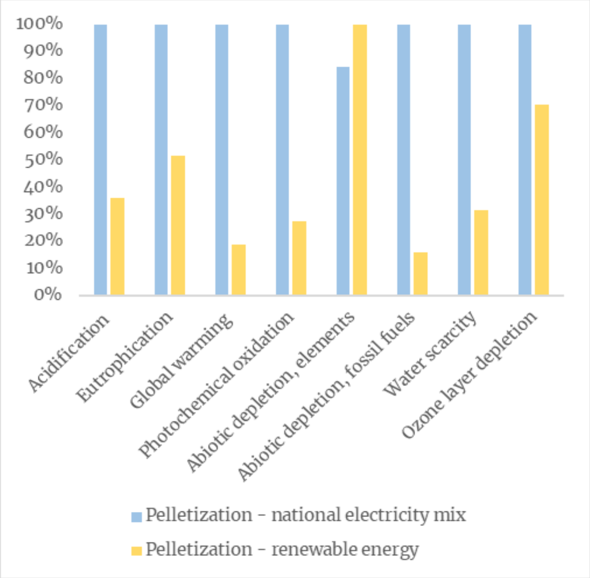

Figure 4. Comparative percentage impact results related to pelletization scenarios

Figure 5 shows the details related to the comparative GWP results of the three different systems and the contribution of each life cycle phase to the total GWP impact values.

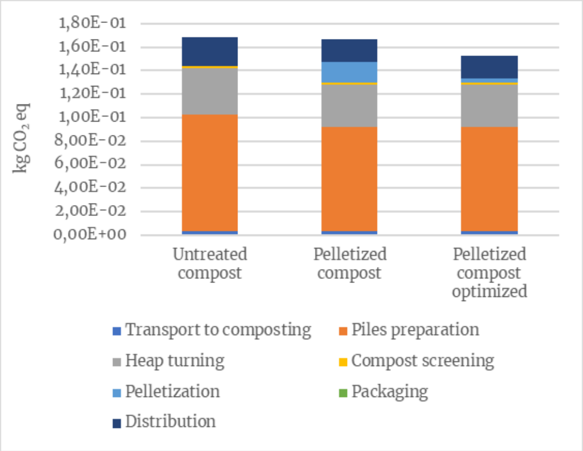

Figure 5. Comparative GWP results with the contribution of each life cycle stage

5. Conclusions

The study aims at evaluating the environmental performance of pelletized compost compared to untreated compost. Being well known its properties related to stability, lack of bad odor, easy handling, and storage and high fertilizing value, an LCA has been carried out considering the fertilizing value as the FU. The scientific literature documents of LCA analyses with mass-based FUs related to compost pellets, and such FUs are not suitable to fully represent the function of the system. With the present study, on the contrary, the fertilizing value has been taken as the FU and it has been demonstrated that, thanks to the higher content of organic carbon compared to untreated compost, the pelletized compost is a sustainable solution also from and environmental point of view. Moreover, choosing renewable energy sources to power the pelletizing machine, it is possible to further improve the environmental performance of the system. Future research will focus on the integration of new aspects in the analysis, such as the inclusion of different nutrients for the definition of the fertilizing value to be used in the FU and the inclusion of the use phase in the system boundaries.

6. Acknowledgements

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