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LIFE CYCLE ASSESSMENT (LCA) OF OFMSW TREATMENT PROCESSES IN AN EFFICIENT WASTE COMPOSTING PLANT

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Abstract

Life Cycle Assessment (LCA) is a standardized methodology critical for the evaluation of environmental impacts of materials and processes, focusing on resource consumption and energy use. In the waste management sector, LCA is essential for identifying optimization strategies, both upstream (selecting recyclable or compostable materials) and downstream (improving waste management processes).
A comparative LCA was conducted and discussed in this paper: the study represents a process LCA which evaluated two scenarios for treatment of the organic fraction of municipal solid waste (namely OFMSW) to produce 1 ton of compost in an Italian composting plant.
From the life cycle analysis, the optimized scenario results in a reduction of the burdens with respect to standard configuration. Finally, a second LCA study compared the optimized composting scenario with hypothetical landfill and incineration alternatives.

Keywords: environmental impacts, LCA, biodegradable and compostable, composting processes, OFMSW

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1. Introduction

Life Cycle Assessment (LCA) methodology is a structured and internationally standardized method for the quantification of environmental impacts of product and processes along their lifetime. The study allows for the identification of the environmental footprint associated with the consumptions of resources and the related emissions during the life cycle of the considered object of the analysis. Developed during the early 70s, in view of an increasing awareness towards the environmental concerns of big scale industrialization, LCA has been applied to several and different technological fields and products, being recognized as a key-tool for the eco-design and climate change mitigation.

As known, the presence of polymers in the globalized market has revolutionized the manufacturing sector and the consequent production of products for everyday life. With low production costs, easy raw materials access and processing and versatility of application, polymers product from oil source are a constant presence in the food industry, thanks for their lightweight and compatibility with diaries. On the other hand, their massive consumption raised up concerns for their disposal fate, since recycling is not possible after food contamination, hence most of these large amounts of tableware and packaging polymer waste at its end of life is sent to landfill. The direct consequence, indeed, is the increase of the waste amount on a global scale and, in turn, the related environmental concerns. For this reason, in the last decades, new raw materials are being considered for the food industry, whose source could be both natural than industrial, but they have the intrinsic property to be reprocessed with food waste once disposed, resulting in a new product: the compost. As a final outcome, these new compostable materials have the advantage to be compatible with food, lightweight and easy processable and, in the end, to reduce the amount of waste in disposal since they could be properly treated with the organic waste in specific plants, called composting site.

Several studies over the last years focused the attention on these new materials, aiming to determine their physical properties, applications and, in particular, their life cycle impacts over the food value chain thanks to the LCA methodology.

Recent studies in the field of composting and the use of compostable tableware have highlighted the significant environmental benefits and potential of these practices. In the last years, research has focused on various aspects, including environmental impact, the efficiency of the composting process, and the role of compostable tableware in reducing waste. For example, Wagas et al. (2023) investigate conventional and emerging composting processes, highlighting mechanisms and influencing factors, emphasizing the advantages, such as reduced groundwater pollution. Similarly, Sokac et al. (2022) discuss about the efficiency of composting that depends on several factors like temperature, pH, moisture content, C/N ratio, particle size, nutrient content, and oxygen supply, and they develop a statistical optimization techniques and mathematical modelling have been developed to enhance these processes.

Azim et al. (2018) addressed the composting to restore organic matter to depleted soils, offering a sustainable fertilization alternative. This review examines the quality and stability of composts from various organic wastes, monitoring, and maturity parameters for different composting methods and raw materials.

Simultaneously, part of the research has evolved to evaluate the environmental impacts of the composting process and the importance of biodegradable and compostable materials., such as Hermann et al., (2011) estimate the carbon and energy footprints of various waste treatment options for biodegradable materials and identified the most environmentally favourable method by comparing home and industrial composting, anaerobic digestion, and incineration. Hottle et al. (2013), provided a comprehensive Life Cycle Assessment (LCA) of compostable tableware made from bio-based polymers, comparing them with conventional petroleum-based alternatives. It discussed the environmental impacts of both materials, focusing on the end-of-life composting process. The study highlighted the benefits and challenges associated with using compostable tableware, particularly in terms of reducing greenhouse gas emissions and supporting sustainable waste management practices. Also, Gisario et al., (2022) conducted a comparative LCA of biopolymer and petroleum-based plastic cups within a composting system. Their study concluded that compostable biopolymer cups have a significantly lower ecological footprint, especially when composting is carried out in optimized facilities. Moshood et al. (2022), examined the sustainability of biodegradable plastics in composting systems, demonstrating that the integration of these plastics can significantly enhance the quality of the produced compost while simultaneously reducing the negative environmental impacts associated with the management of traditional plastic waste. While Cristóbal et al. (2023) focused on practices for compostable plastic packaging waste: impacts, challenges and recommendations were among the aims of this study. In the end, the article assessed the environmental and economic impacts of different waste management schemes for Compostable Plastic Packaging (CPP) using LCA and Costing, in order to inform policy makers on the most effective practices for mitigating climate change and managing financial costs.

Opticompost project (2021-2024) is part of an Integrated Program of Facilitation (namely *Programma Integrato di Agevolazione*, PIA) funded by European Union and Regione Puglia in Italy that aims to develop innovative technological and management solutions to optimize composting processes in particular in presence of items certified according to UNI EN 13432:2002 standard

This paper presents the results of LCA study developed within an Italian regional project aimed at optimizing the composting process. The project seeks to develop innovative technological and managerial solutions for the industrial composting of materials certified according to UNI EN 13432:2002 standard, while simultaneously reducing composting times, increasing production yields, and minimizing process waste.

In this context, the activities described pursue two primary goals: to analyze the environmental performance of the composting process in an optimized scenario that reduces the amount of non-compostable waste, when compared with a baseline scenario and then to evaluate the environmental benefits of decreasing non-compostable material by promoting compostable alternatives. Additionally, a further analysis was conducted to assess the environmental benefits of the new composting process compared to potential end-of-life scenarios prior to the establishment of the facility (landfill, incineration) for comparative purposes.

The article is structured to follow a logical and methodological pathway, beginning with a general overview and the objectives of the activities undertaken. This is followed by the methodology adopted for LCA. The focus then shifts to the application of LCA of the process, evaluating the environmental performance of a specific facility. Subsequently, the paper explores a comparison of different end-of-life management scenarios, highlighting the environmental implications of each alternative. Finally, the conclusions of the study are synthesized, providing a comprehensive overview of the results obtained.

2. Materials and methods

The Life Cycle Assessment (LCA) framework is the method used in this article for the evaluation of the environmental impacts, at product and process level.
LCA is a standardized method used to quantify the potential environmental and human health impacts of a product or service throughout its life cycle. This includes all life cycle phases of the system, from raw material acquisition to end-of-life, (an approach known as "cradle-to-grave").

The LCA methodology is governed by the following standards as ISO 14040: 2006 and ISO 14044: 2006.
The LCA methodology is divided into four phases:

1- *Goal and Scope Definition*: it establishes the purpose of the LCA study, system boundaries, and the functional unit.
2- *Life Cycle Inventory (LCI)*: it involves the data collection of all inputs and outputs of the product system throughout its life cycle. This phase includes all relevant resource use and emissions data.
3- *Life Cycle Impact Assessment (LCIA)*: it evaluates the potential environmental impacts based on the LCI data. This step involves categorizing and assessing the significance of the environmental impacts.
4- *Interpretation of results*: it involves analysing the results of the LCI and LCIA to make informed decisions and provide recommendations. This last phase also includes identifying any uncertainties and limitations in the study.

The process LCA study object of this article is applied to a composting plant sited in Erchie (Italy), aimed at producing high-quality compost for agricultural use, gardens, and green areas. The study compares two different configurations, where the amount of non-composting waste variates.

3. Case-study presentation

The LCA analysis focuses on the composting process at the Heracle facility in Erchie (Italy), aimed at producing high-quality compost for agricultural use, gardens, and green areas. The system boundaries do not include the field application of the produced compost or the associated environmental impacts and benefits, hence the approach is the so-called “cradle to gate”, considering the impacts from raw materials acquisition and processing, until the production of the final outcome of the process, i.e. the compost.

<u>Goal and Scope Definition</u>
The main goal of this analysis is to assess the environmental impacts of the new composting process at Heracle plant, located in Erchie (Italy), by comparing a baseline scenario with an optimized scenario to quantify the associated environmental benefits.

Table 1. Two scenarios related to the LCA Analysis

Baseline Scenario	***Optimized Scenario***
Processing of organic fraction of MSW to produce 1 ton of compost. Non-compostable waste destined for incineration: 22.3% (based on primary data).	Processing of organic fraction of MSW to produce 1 ton of compost. Non-compostable waste destined for incineration: 7.8% (based on primary data).

<u>Functional Unit</u>:
The functional unit (FU) considered for the LCA study is **1 ton of compost** output from the composting facility.

<u>System Boundaries</u>:
The system boundaries encompass the compost manufacturing phase, starting from the extraction and processing of raw materials up to the production of compost, following a *'cradle to gate'* approach.

The analyzed system (Fig. 1) can be divided into a 'primary system' (foreground system, *dark blue*), which includes processes directly controlled by Heracle facilities, and the 'secondary system' (background system, *light blue*), which includes all upstream and downstream processes of composting, modelled based on secondary data (databases, literature, etc.).

Fig. 1. System boundaries of the analysis

Assumptions and Limitations

The following assumptions were made for the study:

- Only the transport of the organic fraction of municipal solid waste (OFMSW) was considered, with an average inter-provincial distance of 50 km from the Heracle site.
- Secondary raw materials used in the composting process, i.e., OFMSW (for compost production) and pruning residues (for biofilter construction), were considered to have zero impact, following the cut-off methodological approach.
- The facility is equipped with a gas effluent treatment system (wet scrubber + biofilter); consequently, gaseous emissions are considered negligible.

LCIA Method and Impact Categories

The method chosen for the environmental Life Cycle Impact Assessment (LCIA) in this analysis is the Environmental Footprint (EF 3.0) method, including 16 specific impact categories.

Description of the case study.

Subject of Analysis: Heracle plant in Erchie (Italy)

The Heracle facility in Erchie was authorized in 2015 and built after 2016. Following regulatory adjustments, the facility was redesigned into 20 biocells to enhance the treatment process, improving internal controls and better track of product flow. The plant covers the disposal basin of the Brindisi province and the municipality of Lecce, in the southern Italy. It includes a technical area with offices, a control room and a system for stormwater and sanitary wastewater treatment. Indeed, stormwater is re-used for irrigation, while sanitary water is partially treated and reintegrated into the system process**.**

Process description

The composting activities in the plant object of this study are distributed as follows:

- *Reception of OFMSW*: Organic Fraction of Urban Solid Waste (OFMSW) is received at the plant, weighted and verified.
- *Unloading in the Pit:* OFMSW is onloaded into a pit with odour control.
- *Mixing:* OFMSW is shredded for uniformity.
- *Transport to Cells – Activation – Maturation:* The shredded material is transferred to one of 20 maturation biocells (45x7 meters each, 800 m³ capacity). The process includes a 30-day activation phase and a 60-day maturation phase. Each biocell is equipped with fans to maintain proper aeration and prevent odour release. The compost is screened to remove impurities before refining.
- *Screening:* After 90 days of maturation, the compost is screened to remove impurities and refine the material.
- *Refinement:* The screened material is placed in the refining chamber. If it meets legal standards, it is packaged and sold as compost.
- *Gas Emissions Treatment:* The plant is maintained under negative pressure to prevent odours from escaping. Gas emissions are processed through wet scrubbers and a wood bark biofilter.

4. Results and discussion

The present chapter discusses results of the LCA, comparing the two different scenarios (baseline *vs* innovative) of the composting process. Results are calculated and expressed using Environmental Footprint (EF) 3.0 impact assessment indicators.

The following hotspot analysis assesses the results of the LCA study on the composting plant, covering the life cycle of 1 ton of compost (functional unit). In Fig. 2, results for the baseline scenario are evaluated.

Fig. 2. Process LCA at baseline scenario: hotspot analysis

The contribution analysis outlines a quite homogeneous distribution of the different inputs of the baseline scenario at Heracle plant; however, major contributions are remarkable. In particular, the **treatment of non-reusable waste** (whose fate here is incineration) has the major share of impacts. This parameter is one of the key-points of the implementation, so its improvement could provide important benefits to the whole environmental impact assessment of the process.

In addition, also **electrical energy consumption** has a relevant share in the impacts, and it is used for the whole management and operation of the plant (i.e. equipment, services, lighting, etc.), as well as fuels for the mobility inside the site (e.g. forklift).

Finally, a negative value is observed for Water use indicator, due to the **wastewater treatment**: this results, quite expected, is a benefit for the process, because the wastewater could be treated and reused inside other purposes (e.g. agriculture), reducing the need of fresh water and resulting in a resource saving.

Following Fig. 3, instead, reports the LCA hotspot analysis on the optimized scenario for the composting plant.

Fig. 3. Process LCA at optimized scenario: hotspot analysis

The hotspot analysis on the optimized scenario LCA results expresses again a distribution between the different contributions, but with a remarkable difference with respect to the baseline scenario. Indeed, the share regarding the **treatment of non-reusable waste** is significantly reduced with respect to baseline: this evidence is caused by a substantial decrease of the non-compostable material (up to the 7.8% of the OFMSW), thus resulting in an important reduction of the environmental impacts associated with its incineration.

The other input flows, as **electricity consumption** or **diesel fuel**, are substantially the same as for the baseline scenario, since the overall management of the plant is quite unchanged.

Moreover, the resource saving related to **wastewater treatment** is consolidated (about 5%), whose benefit is linked with the nature of the treated product and its possible re-use in place of the virgin source.

<u>Scenarios comparison</u>

The comparison assessment of the LCA results for baseline and optimized scenarios of composting process is graphically represented by Fig. 4. The selected functional unit is the same for the two LCA studies, i.e. **1 ton of compost**.

Fig. 4. Comparative assessment of LCA results for baseline and optimized scenario

Comparative assessment outlines a remarkable improvement of the environmental profile of the composting plant in the innovative scenario. Indeed, almost all the selected EF 3.0 impact indicators report an important reduction in the new configuration, with respect to the status-of-the art. This evidence is due to the decrease of the non-compostable material on the whole conveyed waste to the composting site and, thus, the amount to be sent to incineration is lower. Therefore, a global reduction of the impacts is observed for the whole optimized composting process for the selected functional unit. Hence, a better quality of the conveyed waste allows for a remarkable improvement of the environmental performances of the composting process in Heracle plant at Erchie (Italy).

In particular, Land use and Resource use, fossils could be found among the highest expressed values in the impact indicators observed for both scenarios. They are strictly correlated with the energy inputs of the processing plant (e.g. electricity, fuels, etc.), which are mostly taken from the national grid mix, without the support of green sources. As a possible further improvement and suggestion, the use of renewable electricity (e.g. from a photovoltaic plant) could be a strategic action for an additional reduction of environmental indicators associated with energy consumption of the composting site.

An additional comparative LCA analysis has been conducted to evaluate the environmental profile of composting plant (in its innovative configuration) when compared to alternative waste fate available before the plant construction in the same geographical area. In absence of the composting plant, indeed, the OFMSW has two options of treatment: 1) landfill; 2) incineration. The functional unit of the LCA study is **1 ton of OFMSW**, to be treated at its end of life (EoL). Table 2 reports the different alternatives of comparison.

Table 2. Parameters for the comparative EoL LCA study

Parameter	**EoL 1) Landfill**	**EoL 2) Incineration**	**EoL 3) Composting (optimized)**
Functional Unit (FU)	1 ton of OFMSW	1 ton of OFMSW	1 ton of OFMSW
Average distance for transports	30 km (avg in Brindisi province)	90 km (avg Brindisi to Massafra, nearest incineration plant)	50 km (avg Brindisi to Lecce province)

Comparative assessment of the different EoL scenarios is reported in Fig. 5, for 1 ton of OFMSW. The LCA results are calculated according to the EF 3.0 methodology.

Fig. 5. Comparative LCA for different EoL scenarios

Histogram of comparison outlines the difference in terms of environmental impacts for the 3 different EoL scenarios: landfill, incineration and composting in optimized configuration. In particular, the *ex-ante* scenarios (landfill, incineration) are both highly worse with respect to the composting alternative. Considering the peculiarity of the geographical area under analysis (e.g. average distance from the disposal plants, OFMSW transports inter- or infra- cities, disposal attitudes), it is possible to observe that the composting of 1 ton of OFMSW reports a reduction (sometimes very high) of the environmental impact indicators when compared with the two other EoL alternatives.

As a consequence, this comparative LCA on the different waste fate scenarios proves that the *ex-post* presence of the composting plant in Brindisi area allows for a significant advantage in terms of environmental performance of the OFMSW disposal process with respect to the *ex-ante* alternatives (landfill, incineration), whose burdens could be remarkably higher.

6. Concluding remarks

The present paper discusses a Life Cycle Assessment (LCA) study conducted as part of the Opticompost project. The aim of the project is to develop innovative technological and managerial solutions to optimize the composting process of items certified according to UNI EN 13432:2002 standard and to improve composting times, production yields, and reduce waste.

The study reports an evaluation of environmental performance of the composting process at the Heracle facility. The results demonstrate a significant improvement in the optimized configuration, with an average reduction in environmental impacts of about 25%, and up to 61%. Further comparisons with alternative scenarios, such as landfill or incineration, show higher environmental impacts compared to composting alternative.

In summary, the study confirms that composting is a waste treatment solution with significant environmental benefits, where several variables influence the final outcome, some of which are beyond the control of facility operators. The increase in compostable materials on the market and the adoption of Directive (EU) 2019/904 is expected to further improve the composting process.

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