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Systematic Review

Systematic Review and Meta-Analysis on the Use of LCA to Assess the Environmental Impacts of the Composting Process

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Abstract: Following the industrial revolution, major economic and populational growth took place, and, therefore, solid waste generation increased exponentially. Nowadays, waste management still generates major impacts because the current wide offer of waste management strategies includes many solutions that produce suboptimal results, such as landfill or waste incineration. From a circular economy perspective, composting is a potentially sustainable option to treat the organic fraction of solid waste and has the advantage of recycling many organic compounds that can be reintroduced into the natural processes. This study aimed to provide a meta-analysis using the Life Cycle Assessment (LCA) method to evaluate the impacts of composting by performing a systematic literature review of the diversity of approaches and assessing environmental impacts. The results of the impact assessment were highly dependent on the choices made over the system boundary and the functional units. The most cited environmental impacts were Global Warming Potential, Acidification Potential, Eutrophication Potential, Photochemical Oxidation Potential, and Ozone Layer Depletion, as gaseous emissions from the transport and decomposition represent the main contributors to these categories. Using a smaller dataset and evaluating the use of the CML method and the most cited impacts categories, it was found that In-vessel Composting and Home Composting were considered the best environmental options among the studied composting methods. Composting environmental impacts were also highly related to the use of non-renewable energy sources, which puts composting at a disadvantage when compared with the use of anaerobic digestion. Such results emphasize the benefits of using these waste management technologies as complementary instead of substitutes.

Keywords: composting; Life Cycle Assessment; literature review; metadata analysis; environmental impacts

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1. Introduction

Organic solid waste is often classified at an institutional level according to its characteristics and divided into organic fraction municipal solid waste (OFMSW), food waste (FW), yard waste (YW), green waste (GW), organic household waste (OHW), and vegetables [1]. Regardless of how waste is classified, it is paramount to apply appropriate techniques that can lead to recovery of material from it, thus avoiding deposition in landfills [2].

In 2018, only around 5.5% of the waste produced worldwide was recovered through composting [3]. Composting is an appropriate way to generate a product from biowaste that replaces non-renewables with biological resources, according to the principles of the Circular Bioeconomy [4,5]. Diverting waste to composting has the potential to alleviate the impact on climate, reduce greenhouse gases emission, and offer great potential in establishing a circular waste management system when based on a well-planned waste management strategy [6]. Any amount of homemade compost is important to decrease the amount of organic waste that is sent to the landfill.

The composting process occurs through the biological degradation of organic matter by aerobic microorganisms. This biodegradation takes place naturally in the soil, but in the composting process, it is enhanced under controlled conditions [7]. With a reduction of up to 50% of the initial volume, a product of the conversion of organic matter is a compost rich in nutrients, which can be used as fertilizer [1].

During composting, aerobic microorganisms decompose organic material, consume oxygen, and release carbon dioxide, heat, and water vapor [8,9]. The aeration and the ideal temperature reached in an active composting cell are capable of eliminating pathogen microorganisms and most plant seeds [10]. The advantages of this technique are, once the compost is produced and incorporated into a soil, it promotes the incorporation of carbon, the transformation of chemical compounds into nutrients available to plants, and it improves the structure of the soil; it is a substitute for substances that emit atmospheric emissions (e.g., peat) [7].

There are many composting methods, the most common are the use of windrows, passive composting piles, aerated static piles, in-vessel, rotary drum composters, bioreactors, and composting piles [11–13]. The basic composting parameters such as humidity, pH, and C/N need to be controlled before starting the process, as they influence the microbial development and degradation of organic matter [7,9]. The ideal conditions for composting include the introduction of a mix of materials with a humidity between 55–80%, pH values ranging 5–8, and a C/N ratio in the range 20–45 [14]. The duration of the composting process ranges from 20 to 90 days, depending on the method that is used, the process conditions, and the desired quality and maturity of the final compost [11].

Even though composting is an aerobic process, it can emit important concentrations of greenhouse gases that are often neglected, like methane (CH_4) and nitrous oxide (N_2O) [15]. It is known that during composting, residual amounts of CH_4 are emitted, formed in anaerobic pockets due to poor aeration [1]. The N_2O forms during incomplete nitrification/denitrification processes where there is a lack of O_2 or nitrate/nitrite accumulation in the compost pile [16]. Carbon dioxide emissions are considered biogenic because they are of natural and non-anthropogenic origin and, therefore, are not taken into account by some authors [7,9].

Life Cycle Assessment (LCA) is a systematic process used to assess environmental aspects and impacts from the life cycle of a product, service, and/or process [17]. It is known as an approach that studies the life cycle stages of the product. To its full extent, it treats the life cycle from a “cradle-to-grave” approach, because it can be conducted from the extraction of raw materials to the final disposal. In addition, LCA evaluates the environmental impacts of the use of resources and emissions and the discharges of substances generated by the products, services, and processes analysed [17]. It is worth mentioning that the ISO standards, such as ISO 14040:2006 and 14044:2006, do not aim to fully standardize the LCA as a single method, instead they provide a framework that may be adaptable to the intended study [18].

A LCA work consists of four phases: definition of the goal and scope, inventory analysis, impact assessment, and the interpretation phase.

The LCA method was used to evaluate the environmental impacts of the use of different waste management technologies, such as recycling, composting and anaerobic digestion plants, landfilling, and waste incineration, contributing to its improvement in both the public and private sectors [19]. The target audience of LCA in waste management are companies active in local waste management that provide outsourced services to government agencies and that are responsible for sustainable and economic decisions [20].

From a midpoint perspective, the environmental impacts from the use of solid waste management technologies can be grouped into multiple environmental categories, such as global warming potential (GWP), eutrophication potential (EP), acidification potential (AP), photochemical oxidation potential (POP), human toxicity potential (HTP) or ozone layer depletion (OLD) [1,21,22]. Additional options include the use of endpoint methods looking at environmental impacts from a cause-effect chain perspective.

This article presents a systematic review of the literature and a metadata analysis addressing the use of LCA to evaluate the environmental impacts of diverse composting systems. The main objective of this article was to address multiple composting methods and the different choices made regarding LCA processes, trying to make sense of the diversity that can be found in this line of research.

We reviewed 56 articles and evaluated 11 criteria of information: year of publication; country of publication; goal and scope; feedstock type; functional unit; system boundaries; data collection; impact assessment method; impact assessment and interpretation software; impact category results (mid- and endpoint); and the main results. This article is divided into two parts: the first addresses the LCA attributes used by the articles to assess composting systems. In the second, a subset of data is used to address the impact assessment results, considering the differences among the solid waste treatment techniques and the main mitigation measures proposed.

2. Methodology

This systematic review was developed considering three phases: planning, execution and summarization [23,24]. In the first phase, planning, a protocol was created containing valuable information for the systematic review, such as the databases to be searched, the keywords used as search terms, the inclusion and exclusion criteria, quality and information extraction and other topics of interest. In the second phase, execution, the relevant primary studies were identified and selected, through searches for terms in the databases and synthesis of the extracted data. Finally, in the third phase, summarization, data from the studies were summarized and reported [25].

The State of the Art through Systematic Review (StArt), R Studio and Microsoft Excel tools, and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement was used for modelling and data processing [25–27].

2.1. Planning

First, a detailed protocol was developed to describe the method that was applied in this systematic review. This protocol contained: the objective, main question, research database, search terms/keywords and selection criteria for exclusion, quality, and information extraction fields (Table 1).

Table 1. Methodological structure of the protocol summary for the implementation of the systematic literature review phase.

Objective	The Systematic Literature Review approach provides the method to make a literature review on the use of LCA to assess the environmental impacts of the composting process.
Main question	How is the LCA used to assess the environmental impacts of the composting process?
Research database	Scopus and Web of Science
Search terms/keywords	LCA or Life Cycle Assessment and Composting
Definition of Exclusion Criteria, Quality Criteria, and Information Extraction Criteria	

The StArt tool was used to guide and support the handling of the protocol and organization of the systematic review. This tool was created by LaPES-Software Engineering Research Lab from Universidade de São Carlos, to allow the application of a systematic review protocol [25]. The tool is divided into: Planning, Execution, and Summary.

2.2. Execution

The chosen keywords were searched for in article titles, summaries, and keywords as found in the selected databases. The search in both databases was unlimited by date range, however, results were retrieved for publications between 1995 and 2022. A total of 1,370 documents were found, 749 (55%) found on the Web of Science and 621 (45%) on Scopus. From these overlapping data, 453 duplicate records were removed. In the next step, seven predefined Exclusion Criteria (EC) were applied (Table 2). These Exclusion Criteria were defined to exclude articles that were not in accordance with the specificity of this research. As a result, 95 articles advanced to the next stage.

Table 2. Definition of exclusion criteria.

Criteria	Description of Exclusion Criteria
EC1	Incomplete articles will be excluded.
EC2	Works that did not include search terms/keywords in the title and abstract were excluded.
EC3	Articles from non-indexed conferences were excluded.
EC4	Review articles were excluded.
EC5	Works that do not use the composting process were excluded.
EC6	Works that did not use solid organic waste were excluded.
EC7	Works that did not use only LCA were excluded.

The 95 articles underwent a predefined Quality Criteria (QC) analysis (Table 3) based on a more detailed qualitative analysis of the studies, selecting those articles that unequivocally meet the criteria. From this, 38 articles were excluded, and the remaining 56 articles advanced to the Information Extraction and Summarization phases and are part of this systematic review.

Table 3. Quality Criteria of retrieved studies.

Criteria	Description of Quality Criteria	List to Choose from
QC1	Was the article written coherently according to the proposed content?	Yes, No
QC2	Was the LCA approach reported objectively?	Yes, No
QC3	Was the use of the LCA explicitly mentioned?	Yes, No
QC4	Where there were practical applications, have they been described in detail?	Yes, No
QC5	Where there were practical applications, has the inventory been described in detail?	Yes, No

After quality control, the articles were analysed through careful reading, applying 11 predefined information extraction criteria to extract the most relevant information: year of publication; country of publication; goal and scope; feedstock type; functional unit; system boundaries; data collection; impact assessment method; impact assessment and interpretation software; impact category results (mid- and endpoint); synthesis of results (Table 4).

Table 4. Information Extraction Criteria to be worked on in this systematic review.

Field	Content Selection
Year of publication	Specific to each study
Country of publication	Specific to each study
Goal and scope	Specific to each study
Feedstock type	FW (Food Waste), GW (Green waste), OFMSW (Organic Fraction of Municipal Solid Waste), OHW (Organic Household Waste), V (Vegetables), (FL) Fruit Leftovers, YW (Yard Waste)
Functional unit	According to the objective of the study

Table 4. *Cont.*

Field	Content Selection
System boundary	cradle-to-grave, cradle-to-gate, gate-to-gate, gate-to-grave, gate-to-cradle, cradle-to-cradle, bin-to-cradle
Pre-composting	Collection, Transport, Dehydration, Shredding, Anaerobic Digestion
During composting	Transport use, Energy used (fuels and similar), Electricity used, Emissions to air, Emissions to water, Water consumption, Emission to water, Leachate
Post-composting	Compost, Storage, Organic fertilizer, Packaging, Distribution, Application, Post-application
Data collection	Primary and/or Secondary
Impact assessment method	CML-IA, EDIP 2003, EPD 2013, EPS 2000, IMPACT 2002+, ReCiPe, ILCD 2011, TRACI, IPCC 2013, lime 2, Eco-Indicator
Impact assessment and interpretation software	SimaPro, GaBi, OpenLCA, Umberto, Excel, WRATE, EASETECH, LACSD, EASEWASTE, STAN, TOTAL
Impact category results (midpoint)	(GWHH), Global warming Human health; (FPMF), Fine particulate Matter formation; (HCT), Human carcinogenic toxicity; (HN-CT), Human non-carcinogenic toxicity; (GWTE), Global Warming Terrestrial Ecosystems; (GWFE), Global warming Freshwater ecosystems; (TA), Terrestrial Acidification; (TE), Terrestrial Eutrophication; (FE), Freshwater Eutrophication; (ME), Marine Eutrophication; (TEco), Terrestrial Ecotoxicity; (FEco), Freshwater Ecotoxicity; (MEco), Marine Ecotoxicity; (GWP), Global Warming Potential; (AP), Acidification Potential; (POP), Photochemical Oxidation Potential; (EP), Eutrophication Potential; (HT), Human Toxicity; (OLD), Ozone Layer Depletion; (AD), Abiotic Depletion; RD), Re-source Depletion; (WL), Waste Landfill; (CC), Climate Change; (ALOP), Agricultural Land Occupation Potential; (WDP), Water Depletion Potential; (FDP), Fossil Depletion Potential; (IRP), Ionizing Radiation Potential; (MDP), Metal Depletion Potential; (CED), Cumulative Energy Demand; Smog; Carcinogens, (N-Carcinogens), Non-carcinogens, (RE), Respiratory Effects; Ecotoxicity; (NLT), Natural Land Transformation; (ULO), Urban Land Occupation; (N-ReR), Non-Renewable and Renewable; (SWU), Stressed Water Use; (NE), Nutrient Enrichment; (ER), Energy Resources; (NEBR), Net Energy Balance Ratio; (BCR), Benefit Cost Ratio; (LU), Land Use.
Damage category results (endpoint)	Human health (HH), Ecosystems, Resources, Climate Change
Synthesis of results	According to the objective of the study

The information extraction criteria were defined according to the instruction of the four phases of the LCA from the perspective of the composting process (Figure 1) [28].

In phase one of the LCA, goal and scope, criteria regarding the definition of scope, type of feedstock, functional unit, and system boundaries were included.

In phase two, inventory, the criterion of data collection was included, to verify if the articles used primary and secondary data or only secondary data (data from the literature) for their inventories.

In phase three, impact assessment, the criteria included the selection of impact categories, category indicators and characterization models.

In phase four, interpretation, the criteria used were the extraction of results from the impact categories and the synthesis of study results.

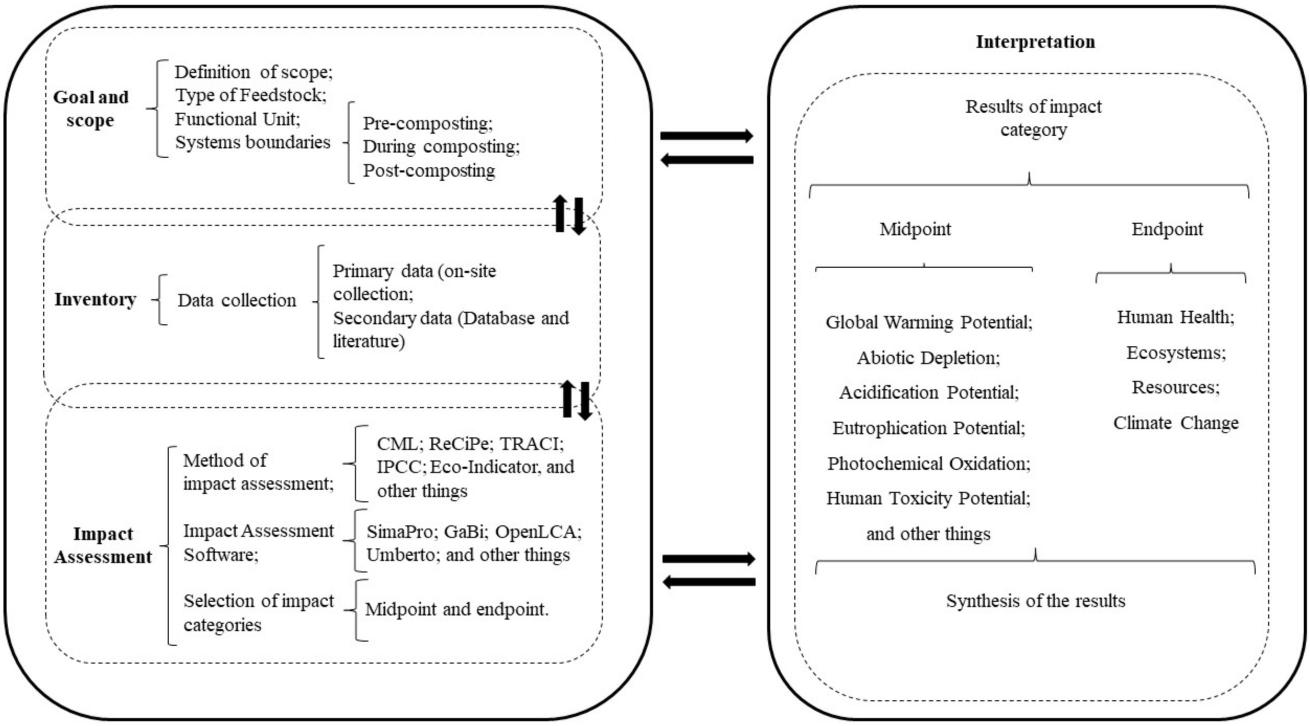

Figure 1. Life Cycle Assessment framework of the composting process.

PRISMA Statement

The PRISMA statement was developed to help perform systematic reviews, addressing why the review was done, what the authors did, and what they found, through the identification, selection, evaluation, and synthesis of studies [26,29]. This systematic review used the PRISMA statement to conduct the protocol and apply the predefined criteria for the selection of the most relevant studies. Registers after applying the exclusion and quality criteria are illustrated in Figure 2.

2.3. Summarization

In the third and final step, summarization, data from the selected articles were identified, organized, and filtered. The data used in this study was plotted in analytical charts, and finally, the results were discussed by category in the Qualitative and Quantitative Analysis (Section 4).

To represent the data quantitatively, only the CML impact assessment method was considered to avoid misinterpretations, ensure coherence, and allow comparison between studies.

A one-way analysis of variance (ANOVA) was performed in SPSS software to determine whether any statistically significant differences between the impact category data, considering a significance level of 0.05.

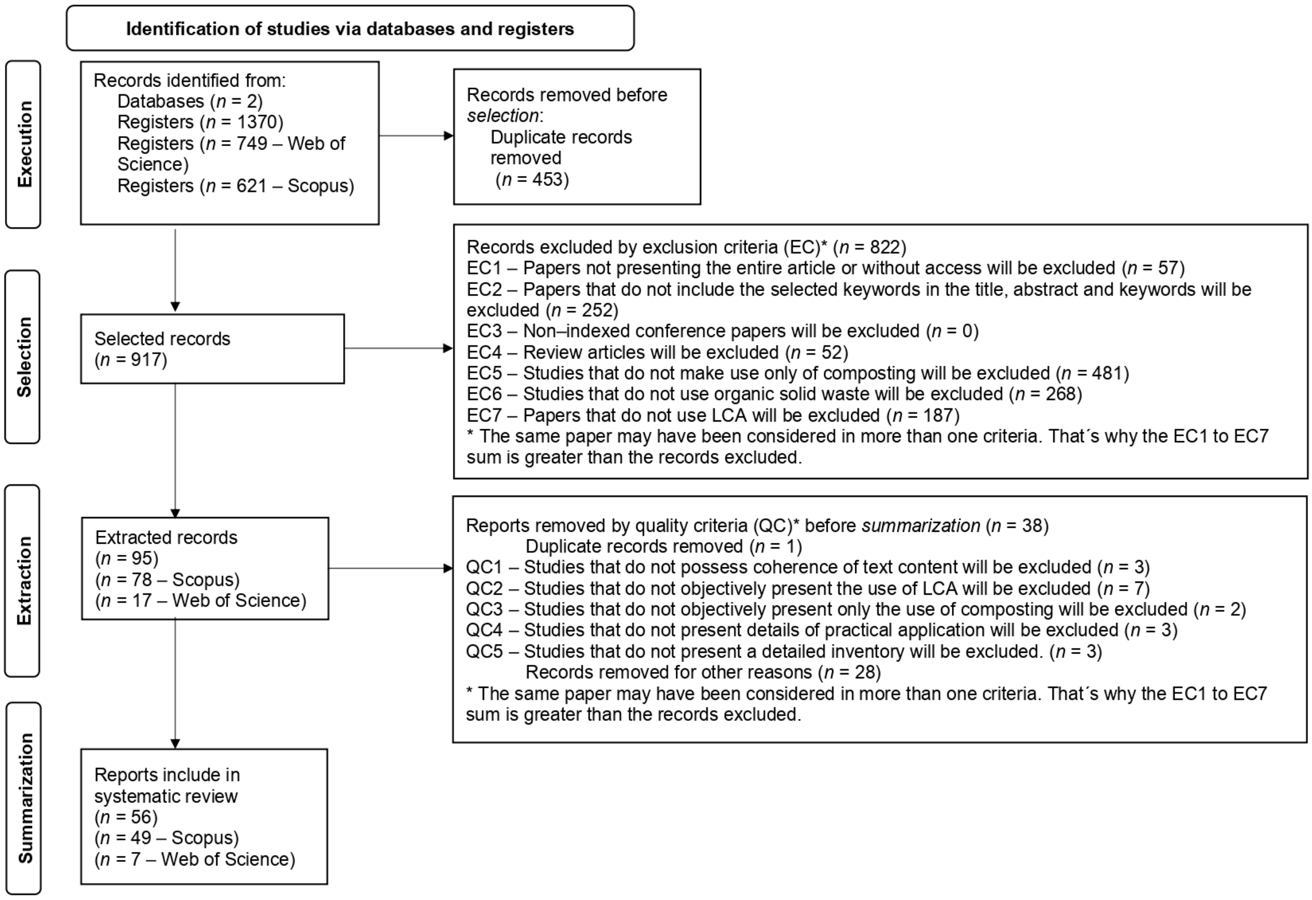

Figure 2. PRISMA 2020 flow diagram for new systematic reviews which included searches of databases and registers only. Source Adapted from [26].

3. Bibliometric Analysis

3.1. Keywords

From the data generated by the R tool, about 1805 keywords were identified in total. Figure 3 shows the 25 most used keywords in the selected articles, frequency, and relative contribution. The keywords are associated with the topic and the methodology used by the authors in the articles.

3.2. Publication Period

From the selected dataset, the trend in the number of publications addressing LCA as applied to composting over 27 years is presented in Figure 4. The publications began in 2005 and had a first significant increase in number between 2008 and 2010, however, numbers have fluctuated over time with a slight tendency towards growth (Figure 4). This growth indicates the relevance of the subject in the scientific community and the importance of applying the LCA approach.

Figure 3. The 25 most relevant keywords.

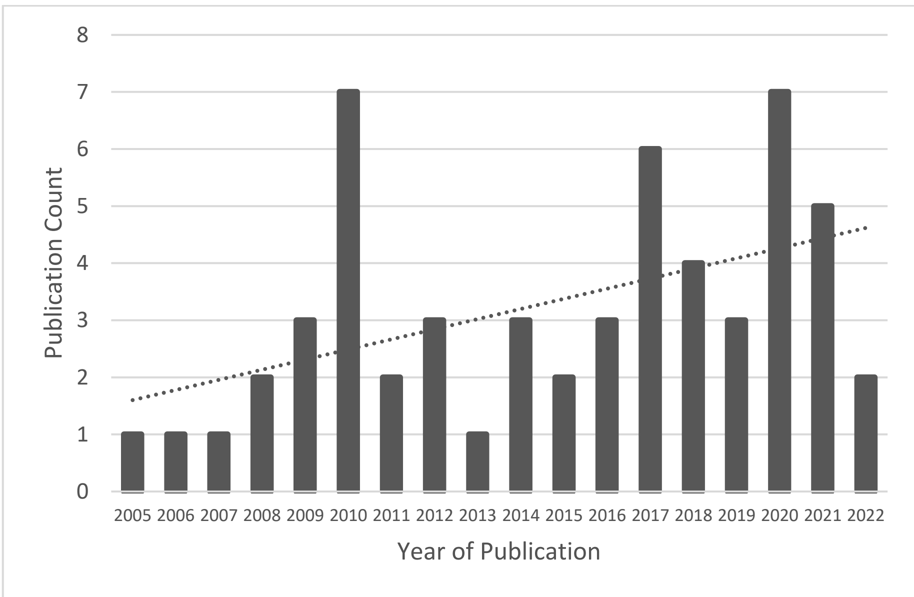

Figure 4. Publications per year and the frequency trend line (Timespan 1995:2022).

3.3. Geographical Location of Publications

Regarding the number of publications by geographic location or country (Figure 5): Spain had the highest number of publications (16%), followed by Italy (14%), the United States (13%), Denmark (9%) and Malaysia (7%) (Table 5). These five countries account for about 59% of the material analysed. Consequentially, the continent with the highest number of publications (Table 5) was Europe (52%), followed by Asia (27%), North America (13%), Oceania (5%), and South America (4%).

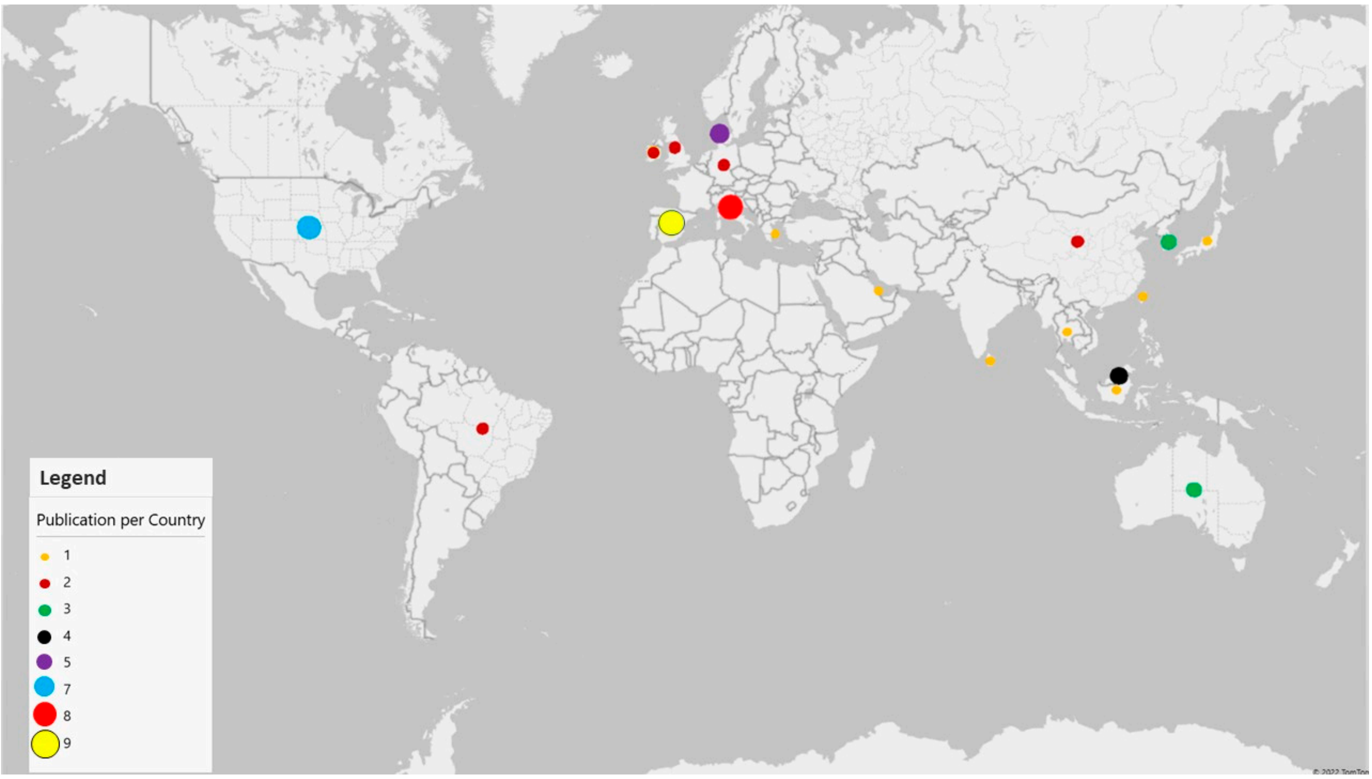

Figure 5. Published papers per country over the years.

Table 5. Published papers by continent and countries.

Continent	No. of Publications	% of Publications
Europe	29	52
Asia	15	27
North America	7	13
Oceania	3	5
South America	2	4
Country	No. of Publications	% of Publications
Spain	9	16
Italy	8	14
United States	7	13
Denmark	5	9
Malaysia	4	7
Australia	3	5
South Korea	3	5
Brazil	2	4
China	2	4
Germany	2	4
Ireland	2	4
United Kingdom	2	4
Greece	1	2
Indonesian	1	2
Japan	1	2
Qatar	1	2
Sri Lanka	1	2
Taiwan	1	2
Thailand	1	2

4. Qualitative and Quantitative Analysis

This section discusses the information extracted after applying the Information Extraction Criteria to the selected 56 articles.

4.1. Goal and Scope

The goal and scope definition is the first stage of the LCA, where the objective of the study, the system boundary, the functional unit, and the level of detail are determined [28].

The definition of the LCA's objective is contingent on the singularity and depth of each study, which will influence the definition of the system boundary. In the management of organic solid waste, objectives are diverse because they are determined by the type of managed waste, the processes used, and the final application(s) [30]. The objectives of the studies indicated by the authors, as well as the feedstock and functional unit (FU) are presented in Table 6. As the objectives are particular for each study, it was difficult to address them by categories, nonetheless, after careful interpretation, a total of five categories were established. About 22 of the 56 articles established the objective of evaluating the environmental impacts of composting techniques or the use of this method in combination with other organic waste treatment technologies. Approximately 17 of the 56 articles defined the objective of comparing composting techniques with different types of organic waste, and another five defined the objectives only to analyse the environmental impacts of composting organic waste, without any other comparison. The remaining articles established different objectives, without deviating from the main theme, which was the estimation and assessment of the environmental impacts of composting. Most of the studies compared different waste treatment technologies, evaluating the most environmentally sound that could therefore be used for improved environmental management.

Table 6. Objectives, feedstock, and functional unit of the analysed composting processes (cont.).

Articles	Objective	Feedstock Type	FU
[31]	Compare home composting, centralized composting with food wastes and yard wastes, and co-disposal with food and municipal wastes	FW, YW	182 kg (wet)
[32]	Compare the existing waste systems with the proposed integrated approaches.	OFMSW	1 t of waste
[33]	Compare two systems: landfill and recycling (landfill, incineration, composting and feed manufacture).	FW	1 t of waste
[34]	Assess GHG emissions from controlled composting processes.	OHW	1 Mg fresh matter input
[35]	Evaluate existing aerobic plants and compare them with a scenario based on organic waste landfills.	GW, OHW	1 kg of bio-waste input
[21]	Assess the environmental impact of two composting technologies: in-vessel (tunnel) and confined windrow.	OFMSW	1 t of OFMSW
[36]	Evaluate the environmental and energy performance of organic waste from wine production.	GW	1 kg nitrogen
[37]	Determine the overall emission of any chemical compound in large-scale composting.	OFMSW	1 Mg of OFMSW
[38]	Assess the environmental impacts of home composting.	V, FL	1 Mg of waste (LRFV)
[39]	Assess the environmental impacts of home and industrial composting.	OFMSW	1 t of OFMSW
[40]	Compare the environmental impacts of composting with the use of an alternative daily cover (ADC).	YW	1 Mg of yard waste

Table 6. *Cont.*

Articles	Objective	Feedstock Type	FU
[41]	Evaluate and compare different food waste disposal systems from generation to final disposal.	FW	1 t of FW
[42]	LCI of the garden waste composting plant.	YW	1 Mg of wet waste (ww)
[43]	Indicate the energy balances and environmental impacts of some sub-units (recycling of the packaging materials, the treatment of the bio-waste, and the energy recovery from the residual waste).	FW, GW	1 t of feedstock
[44]	Calculate a range of net energy benefit ratios and monetary benefit-cost ratios for harvest and composting scenarios for Hydrilla management.	V	1 ha of aquatic plants harvesting
[45]	Environmental assessment of garden waste management options.	YW	16,220 Mg of garden waste in the year
[46]	Provide useful datasets for LCA studies on the biological treatment of organic waste.	FW, YW	1 Mg of green waste
[47]	LCA on home composting of OHW with LCI data for single-family home composting.	OHW, YW	1 Mg of OHW
[2]	Analyse the impacts of GHGs on organics management	OFMSW	1 t of wet organic matter
[48]	Analyse the environmental impacts and energy consumption of four biological waste treatment plants.	OFMSW	1 Mg of OFMSW and Respiratory Index (RI)
[49]	Quantify the major environmental impacts of a composting system.	FW	1 t of compost
[50]	Compare two household composts and the gaseous emissions from composting.	V	6.8 t. ha^{-1} of cauliflower vegetables
[51]	Analyse the environmental impacts of waste management by combining anaerobic digestion and composting.	FW	kg eq/(per·a)
[52]	Evaluate the effect of the use of compost in crop rotation.	OFMSW	1 commercial t of chard, tomatoes, cauliflower, or onions
[53]	Compare olive oil waste use in energy production and composting options.	GW	1 Mg of olive solid waste
[54]	Compare different organic waste management scenarios.	OFMSW	1 Mg of OFMSW
[55]	Assess the environmental benefits of home composting.	OHW	1 t of organic household waste
[56]	Assess the environmental impacts of food waste management.	FW	1 t of FW
[57]	Quantify the environmental impacts of waste reduction and use compared to the usual scenario.	FW	Annual quantity of waste (1,267,749 t)
[58]	Analyse six alternatives for the composting of the organic waste generated.	OHW	68–90 kg wet waste
[59]	Evaluate the environmental performance of in-vessel composting.	FW	Fresh matter per t (FM) in waste
[60]	Assess the environmental impacts of residential food waste treatment.	OFMSW	1 t of residential waste
[61]	Evaluate the performance of the combined dry anaerobic digestion and composting unit.	OHW	1 t of organic waste
[62]	Assess the environmental impact of FW treatment and compare different scenarios.	FW	1 t of FW

Table 6. *Cont.*

Articles	Objective	Feedstock Type	FU
[63]	Evaluate and compare five different waste treatment methods.	FW	1 t of waste
[64]	Quantify the environmental impacts of three waste management options	FW	1 t of household food waste
[65]	Evaluate the environmental, energy, and economic sustainability analysis of five composting plants.	GW	1 t of compost
[66]	Assess the environmental impact of energy production and waste treatment using AD and composting.	FW, GW	1 t of organic waste
[67]	Assess the implication of the transition of organic waste from a linear economy to a circular economy.	FW, GW	1 kg of organic waste. 1 kg available nitrogen (N).
[68]	Compare open-air composting and static composting on a pile of olive waste.	GW	1 Mg peat or compost.
[69]	Identify the environmental hotspots in two treatment options.	OFMSW	1000 t of organic waste
[70]	Compare the environmental performance of alternative waste management options.	YW	1 t of yard waste
[71]	Analyse the environmental and economic performance of home and centralized composting.	FW, YW	1 Mg (wet weight) of organic waste
[72]	Evaluate the environmental impacts and benefits of composting beds and anaerobic digestion with composting.	FW	1 t FW
[73]	Evaluate the performance of a community-scale aerated static pile composting system.	FW, YW	200 kg/day of organic waste
[4]	Valorise vineyard waste to produce compost.	GW	1 t of waste
[74]	Estimate and compare the environmental impacts of two composting alternatives.	GW	1 t of compost
[75]	Investigate and compare the environmental life cycle impact of waste.	GW	1 piece of carbonized briquette (150 g/unit)
[76]	Assess the environmental and economic sustainability of scenarios for household waste management.	FW	1 t of FW household.
[77]	Compare the environmental impacts and socio-economic effects of composting and compost use.	FW	1 ha of vegetable cultivation. 25 t of FW
[78]	Assess the environmental impacts of composting and composting with landfill.	FW	1 t of FW pre-treated
[6]	Assessment of FW and YW entering the composting site.	FW	1 kg of FW
[79]	Estimate and compare the environmental impacts of three different waste systems.	GW	1 m^3 of compostable materials
[80]	Find a system with lower environmental impacts for the treatment of bio-waste.	OHW	1 t of kitchen waste treated
[81]	Assess the environmental impacts of OFMSW treatment by composting.	OFMSW	1 t of OFMSW
[82]	Develop sustainable management of FW.	FW	1 t of FW (wet basis) treated

4.2. Functional Unit

The functional unit (FU) is the reference unit to which all input and output data must be associated in a mathematical sense [28]. This allows comparison between systems when the functional units refer to the same product and quantity (input or output) [30]. The FU of waste is assigned to the mass of waste processed or of the final output, in this case, the compost.

The choice of the functional unit also depends on the purpose for which the system is intended. When composting is used to process organic waste from a disposal perspective, a functional unit related to the input feedstock mass is more appropriate. If the intention is to address composting from the perspective of waste valorization, the functional unit should be configured to the quality and the mass of the compost [67].

Around 64% of the studies used the FU of one metric ton of waste to be processed (Table 6). Only four (7%) of the studies analysed per ton of compost as a reference. The other 30% of the cases defined the FU with a different unit of measurement (g, kg, hectare, m3), different selected products (kg of nitrogen, aquatic plants harvesting, harvesting and cultivation of commercial vegetables, carbonized briquette) that could not be grouped in the same categories.

The type of waste composted is also relevant due to its diverse biochemical composition that influences key composting factors such as the C/N ratio, moisture content and porosity in the composting process [72]. The waste found in these studies was grouped according to the following categories: Food Waste (FW), Green Waste (GW), Organic Fraction Municipal Solid Waste (OFMSW), Vegetables (V), Yard Waste (YW) and Fruit Leftovers (FL). Almost 30% of the studies evaluated the entry of FW, 19% of OFMSW, and 17% analysed wastes mixed with others.

4.3. System Boundaries

The boundary of the system is a very decisive step because it determines the processes to be included in the analysis. At the system boundary, the flows of mass, energy, and materials are accounted for. This boundary needs to be consistent with the objective of the study because the results of the LCA will be relatable to this definition. The standards ISO 14040 and 14044 establish that the boundary of the system should be defined as cradle-to-grave, cradle-to-gate, and gate-to-gate [17,28].

For the analysed composting articles (Table 7), about 70% did not explicitly define the boundary of the studied systems, which can be caused by the lack of process data, leading to uncertainty and potentially incorrect interpretation of the results. On the other hand, most of the other remaining articles (seven) defined the boundary of the system in a cradle-to-grave approach. This definition covers all the activities necessary for composting, from feedstock extraction (waste collection) to the final use of the compost (application on agricultural land) [4,32]. Another very interesting definition is the cradle-to-cradle assessment, used by two articles. This definition is based on the circular economy perspective, because, unlike the manufacturing process, in the composting process the waste that enters has added value, then results in a new product (compost), thus avoiding the generation of new waste, manufacturing of original products (synthetic fertilizers) and impacts attributed [57,67]. Lin et al. [82] used a less traditional bin-to-cradle system boundary, very similar to the cradle-to-cradle definition, where the processes included waste disposal treatment, waste recovery and production of the value-added by-products.

Table 7. Summary of system boundaries for the inventory analysis of composting.

Article	System Boundary	Pre-Composting	During Composting	Post-Composting
[31]		Shredding, Anaerobic Digestion,	Transport, Energy, Electricity, Emissions to air, Water consumption, Leachates	Compost
[32]	cradle-to-grave	Transport	Energy, Electricity, Emissions to air, Emissions to water,	Compost
[33]			Electricity, Emissions to air, Emissions to water	Compost
[34]			Emissions to air, Leachates	Compost

Table 7. *Cont.*

Article	System Boundary	Pre-Composting	During Composting	Post-Composting
[35]	gate-to-cradle	Collection, Transport	Energy, Electricity, Emissions to air	Compost, Organic fertilizer
[21]			Energy, Electricity, Emissions to air, Water consumption	Compost
[36]		Transport, Shredding	Transport, Energy, Electricity, Emissions to air	Compost, Organic fertilizer,
[37]			Energy, Electricity, Emissions to air, Water consumption	Compost
[38]		Shredding	Transport, Energy, Electricity, Emissions to air, Water consumption, Leachates	Compost
[39]		Collection, Transport, Shredding	Transport, Energy, Electricity, Emissions to air, Water consumption, Leachates	Compost, Distribution
[40]		Collection, Shredding	Energy, Electricity, Emissions to air, Emissions to water	Compost, Organic fertilizer
[41]	gate-to-gate	Collection, Transport, Dehydration, Shredding	Energy, Electricity, Emissions to air, Emissions to water, Water consumption, Leachates	Compost
[42]		Shredding	Energy, Electricity, Emissions to air	Compost
[43]			Electricity, Emissions to air,	
[44]		Collection	Energy	Compost, Organic fertilizer
[45]	cradle-to-grave	Transport, Shredding	Energy, Electricity, Emissions to air	Compost, Organic fertilizer
[46]			Energy, Electricity, Emissions to air	Compost
[47]			Emissions to air, Emissions to water, Leachates	Compost, Organic fertilizer
[2]		Collection, Transport, Shredding	Energy, Electricity, Emissions to air	Compost, Distribution, Application
[48]			Energy, Electricity, Emissions to air, Water consumption, Leachates	Compost
[49]		Collection, Transport	Transport, Energy, Electricity, Emissions to air	Compost, Organic fertilizer, Distribution, Application
[50]	cradle-to-gate	Transport	Energy, Electricity, Emissions to air, Emissions to water, Water consumption, Leachates	Compost, Organic fertilizer Application, Post-application
[51]		Transport	Energy, Electricity, Emissions to air, Emissions to water, Leachates	Compost, Distribution
[52]	cradle-to-gate		Energy, Electricity, Emissions to air, Emissions to water, Water consumption	Compost, Organic fertilizer, Distribution, Application

Table 7. *Cont.*

Article	System Boundary	Pre-Composting	During Composting	Post-Composting
[53]		Transport	Emissions to air	Compost, Distribution, Application
[54]		Collection, Transport	Energy, Electricity, Emissions to air, Water consumption, Leachates	Compost
[55]			Emissions to air	Compost
[56]	gate-to-gate	Collection, Transport, Dehydration, Shredding	Energy, Electricity, Emissions to air, Emissions to water, Water consumption, Leachates	Compost
[57]	cradle-to-cradle	Collection, Transport	Energy, Electricity, Emissions to air, Water consumption	Compost, Organic fertilizer
[58]			Energy, Emissions to air, Leachates	Compost
[59]		Collection, Transport	Energy, Electricity, Emissions to air, Emissions to water, Leachates	Compost, Organic fertilizer
[60]		Collection, Transport, Anaerobic Digestion	Energy, Electricity, Emissions to air, Emissions to water, Leachates	Compost, Organic fertilizer
[61]		Anaerobic Digestion	Energy, Electricity, Emissions to air	Compost
[62]		Collection, Transport	Energy, Electricity, Emissions to air, Emissions to water, Leachates	Compost
[63]		Collection, Transport, Dehydration	Emissions to air, Emissions to water	
[64]	gate-to-grave	Shredding	Energy, Electricity, Emissions to air, Water consumption	Compost, Application
[65]		Collection, Transport	Energy, Electricity, Emissions to air, Emissions to water, Leachates	Compost, Storage, Distribution
[66]		Collection, Transport, Shredding, Anaerobic Digestion	Energy, Electricity, Emissions to air, Water consumption	Compost
[67]	cradle-to-cradle	Collection, Transport	Energy, Electricity, Emissions to air, Water consumption, Leachates	Compost, Organic fertilizer
[68]	cradle-to-grave	Transport, Shredding	Energy, Electricity, Emissions to air	Compost
[69]		Anaerobic Digestion	Energy, Electricity, Emissions to air, Leachates	Compost, Distribution
[70]		Shredding	Energy, Electricity, Emissions to air, Emissions to water, Leachates	Compost, Organic fertilizer, Application
[71]		Collection, Transport, Shredding	Energy, Electricity, Emissions to air, Water consumption, Leachates	Compost, Organic fertilizer, Distribution, Application

Table 7. *Cont.*

Article	System Boundary	Pre-Composting	During Composting	Post-Composting
[72]	cradle-to-grave	Collection, Transport, Shredding	Energy, Electricity, Emissions to air, Emissions to water	Compost, Organic fertilizer, Distribution, Application, Post-application
[73]		Collection, Transport, Shredding	Transport, Energy, Electricity, Emissions to air	Compost, Packaging
[4]	cradle-to-grave	Collection	Energy, Electricity, Emissions to air, Emissions to water, Water consumption, Leachates	Compost, Organic fertilizer, Packaging, Distribution, Application
[74]		Collection, Transport, Shredding	Energy, Electricity, Emissions to air, Emissions to water, Leachates	Compost, Storage, Distribution, Application
[75]	cradle-to-grave	Collection	Transport, Energy, Emissions to air	Compost
[76]	cradle-to-grave		Energy, Electricity, Emissions to air	Compost, Organic fertilizer
[77]		Collection, Transport	Transport, Energy, Electricity, Emissions to air, Water consumption, Leachates	Compost, Organic fertilizer, Distribution, Application, Post-application
[78]	cradle-to-gate	Collection, Transport, Shredding	Energy, Electricity, Emissions to air, Emissions to water, Water consumption, Leachates	Compost, Organic fertilizer
[6]		Collection, Transport, Shredding	Energy, Electricity, Emissions to air, Leachates	Storage, Packaging
[79]		Collection, Transport, Shredding	Energy, Electricity, Emissions to air, Emissions to water, Leachates	Compost
[80]			Electricity, Emissions to air, Emissions to water, Leachates	Compost
[81]			Energy, Electricity, Emissions to air, Emissions to water, Water consumption, Leachates	Compost, Organic fertilizer
[82]	bin-to-cradle	Dehydration, Shredding	Electricity, Emissions to air	

After defining the system boundary, it is necessary to select the processes included within this limit. Although the articles often use the same concepts, there are differences between each system boundary as a consequence of the diversity in the objectives of the studies and data availability [4,32,75]. The classical system boundary of solid waste management begins with waste disposal, that is, at the end-of-life of another product, followed by the processing and conversion stages leading into a new product [4,30]. The composting study system is usually classified into three stages, pre-composting, composting, and post-composting (Figure 6) [1].

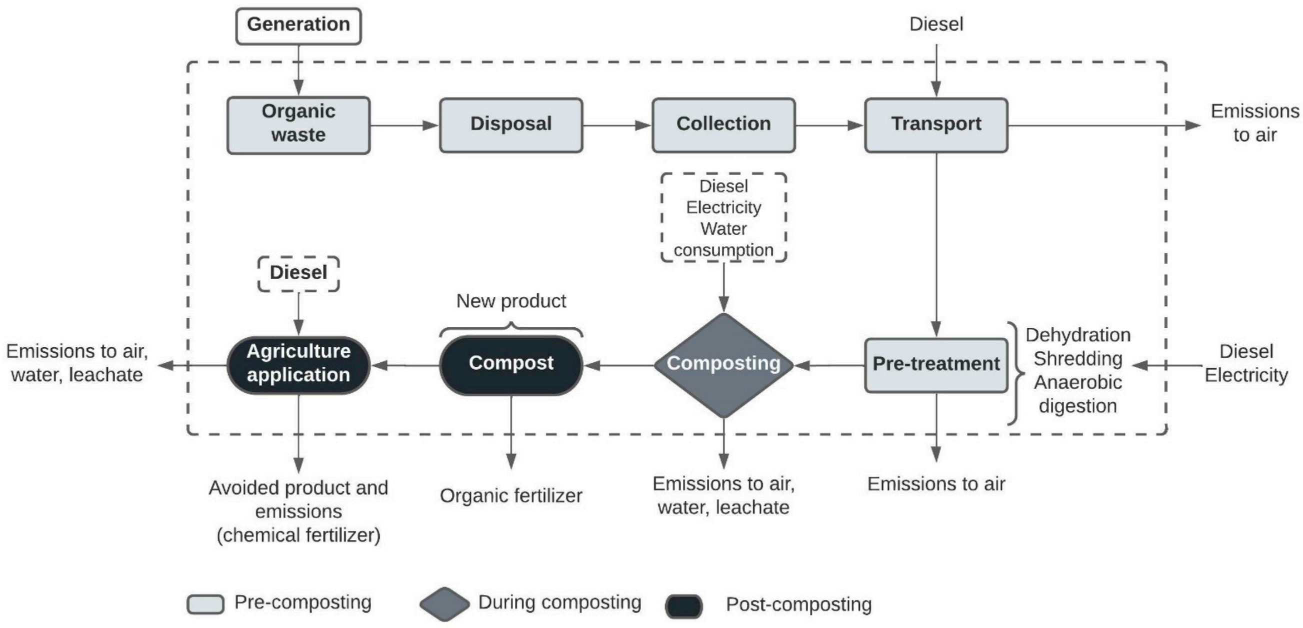

Figure 6. System boundary for the pre-composting, composting, and post-composting stages, in the cradle-to-grave concept.

In the pre-composting stage, the system boundary usually includes the collection, transport, and pretreatment of organic solid waste. During composting, the analysis is conducted considering materials, energy and water use and emissions to the soil, water, and air, associated with the composting process itself. In the post-composting stage, the distribution of the compost and the application is analysed (Figure 6) [1].

Around 13 articles did not include the pre-composting steps in the LCA (Table 7). Of those that included it, only two contained all the expected pre-treatment steps (Collection, Transport, Dehydration, and Shredding). Five articles used anaerobic digestion in the pre-treatment stage and also considered electricity generation from burning biogas, a complementary system, [66,69].

Regarding composting, all articles included a general analysis of the composting process, considering fossil fuel, electricity and water consumption, emissions to the air, wastewater and leachates caused by the process. Generally, the greatest impacts were attributed to this step due to the greater amount of operating input required (fossil fuels, electricity, water) and emissions resulting from the particular process (CO_2, NH_3, CH_4, N_2O, SO_2). Rigamonti et al. [43] only analysed the composting process (without including pre- and post-composting in the system boundary) considering some important variables such as composting yield, nutrient content in compost, and avoid products (inclusion or exclusion of the peat energy feedstock).

Twelve of the 56 studies analysed the application of the compost and, of those, three addressed the application of the compost in agricultural soils, including cauliflower and spinach crops [50,72,77]. The environmental loads from construction, assembly of installations and equipment, are often unaccounted for to ease the comparison between systems, due to a lack of data for inventory, and also because their impacts can be negligible [45,53]. Other articles included capital goods for other waste treatments (anaerobic digestion, incineration) inside the system's boundaries, due to the high contribution to the environmental impacts generated [64,70].

4.4. Inventory Analysis

Inventory analysis is the LCA phase addressing the qualitative and quantitative data of the inputs and outputs associated with each elementary process included in the study system [28]. It involves the collection of primary (field collected at the project site) and secondary (from literature, databases, and software) data necessary to achieve the study objectives.

Most studies (93%) were able to collect primary data and use information specifically for the composting procedure. However, all studies that used primary data supplemented inventories with literature and database information (secondary data). The remaining 6% used only secondary data.

The main limitation found by the articles using secondary data for inventories was the unavailability and uncertainty of process information [40,47,72]. This can lead to overlapping impact categories, erroneous assumptions, and inaccurate adjustments between systems because there are adaptations that may incorporate errors.

4.5. Impact Assessment

The Life Cycle Impact Assessment is the third stage of the LCA [17,28] and provides information regarding the magnitude of environmental impacts.

At this stage, input and output flow data are converted into characterization factors according to the group of resources and emissions assigned to each impact category, calculated by a set of impact indicator scores [83]. The result expresses the contributions to several categories of impacts, such as climate change, eutrophication and scarcity of resources [84].

The methods used to estimate the impacts consider specific characterization factors for each substance multiplied by the values from inventory data and the result is a value expressed in the category indicators [85]. These categories are divided into midpoints and endpoints [83]. Midpoint categories are based on unique environmental issues and are associated with problem-oriented methods. The endpoint categories are concerned with the characterization of the intensity and implications of midpoint impacts and are known by damage-oriented methods [78]. Some impact categories associated with the midpoint and endpoint are presented in Table 8 [86,87].

Table 8. Some midpoint and endpoint impact categories.

Categories midpoint	Ozone Depletion (Stratospheric), Human Toxicity, Respiratory Inorganics, Ionizing Radiation, Photochemical Ozone Formation (Ground Level), Acidification (Land and Water), Eutrophication (Land and Water), Ecotoxicity (Freshwater, Marine, Terrestrial), Land Use, Resource Depletion (of Minerals, Fossil and Renewable Energy Resources, Water, . . .)
Category endpoints	Climate Change (Life Support System), Damage to Human Health, Damage to the Ecosystem, and Depletion of Natural Resources. These Relate to The Three Areas of Protection “Human Health”, “Natural Environment” And “Natural Resources”, respectively.

The LCA framework is often modelled using LCA software, which will quantify and evaluate the environmental loads of the entire system using characterization methods [78,85]. Table 9 presents the characterization methods used in the analysed studies for composting, which includes CML, EDIP 2003, ReCiPe, ILCD 2011, TRACI, IPCC 2013, and Eco-Indicator.

Table 9. Review of the Impact Assessment for composting of the analysed studies.

Articles	Method of Impact Assessment	LCIA Software	Impact Category Results
[31]		Gabi	(TEco) (FEco) (MEco) (AP) (EP) (HT) (CC)
[32]		SimaPro	(GWP) (AP) (POP) (EP)
[33]	CML	IWM	(FEco) (GWP) (AP) (EP) (HT)
[34]			(GWP)

Table 9. *Cont.*

Articles	Method of Impact Assessment	LCIA Software	Impact Category Results
[35]	Eco-Indicator	SimaPro	(GWP) (AP) (POP) (EP) (OLD) (CED) (ER)
[21]		SimaPro	(GWP) (AP) (POP) (EP) (HT) (OLD)
[36]	CML	SimaPro	(TEco) (FEco) (MEco) (GWP) (AP) (POP) (EP) (HT) (OLD) (AD)
[37]		SimaPro	(RE)
[38]	CML	SimaPro	(GWP) (AP) (POP) (EP) (OLD) (AD) (CED)
[39]	CML	SimaPro	(GWP) (AP) (POP) (EP) (OLD) (AD) (CED)
[40]	Eco-Indicator	SimaPro	(AP) (EP) (CC) (FDP) (RE)
[41]		SimaPro, TOTAL	(GWP)
[42]		STAN	(GWP)
[43]	CML	SimaPro	(GWP) (AP) (POP) (HT) (CED)
[44]			(NEBR) (BCR)
[45]	EDIP 2003	EASEWASTE	(TEco) (FEco) (GWP) (AP) (POP) (HT) (NE)
[46]	EDIP 2003	EASEWASTE	(GWP) (AP) (POP) (NE)
[47]	EDIP 2003	EASEWASTE	(TEco) (FEco) (GWP) (AP) (POP) (HT) (SWU)
[2]		LACSD	(GWP)
[48]	CML	SimaPro	(GWP) (AP) (POP) (EP) (HT) (OLD) (AD)
[49]	TRACI	SimaPro	(GWP) (AP) (EP) (OLD) (Smog) (Carcinogens) (N-Carcinogens) (RE) (Ecotoxicity)
[50]	CML	SimaPro	(GWP) (AP) (POP) (EP) (OLD) (AD) (CED)
[51]	EDIP 2003	EASEWASTE	(GWP) (AP) (POP) (HT) (OLD) (Ecotoxicity) (NE)
[52]	CML		(GWP) (AP) (POP) (EP) (OLD) (AD) (CED)
[53]	CML, ReCiPe	OpenLCA	(GWP) (AP) (POP) (EP) (HT) (OLD) (FDP) (IRP)
[54]	CML	SimaPro	(GWP) (AP) (POP) (EP) (OLD) (AD)
[55]	CML	SimaPro	(TEco) (FEco) (MEco) (GWP) (AP) (POP) (EP) (HT) (OLD) (AD)
[56]	CML	STAN, TOTAL	(GWP) (AP) (POP) (EP)
[57]	CML	Gabi	(GWP) (AP) (EP)
[58]	ReCiPe	IWM	(FPMF) (FEco) (HT) (OLD) (CC)
[59]	TRACI	SimaPro	(GWP) (AP) (EP) (OLD) (FDP) (Smog) (Carcinogens) (N-Carcinogens) (RE) (Ecotoxicity)
[60]	ILCD 2011	EASETECH	(TA) (TE) (FE) (ME) (OLD) (CC) (FDP)
[61]	ILCD 2011	EASETECH	(GWP)
[62]	CML	SimaPro	(TEco) (FEco) (MEco) (GWP) (AP) (POP) (EP) (HT) (OLD) (AD) (CED) (LU)
[63]	Eco-Indicator	SimaPro	(AP) (EP) (CC) (Carcinogens)
[64]	ILCD 2011	Wrate	(FPMF) (TA) (TE) (ME) (GWP) (POP) (OLD) (RD) (FDP) (IRP) (Carcinogens) (N-Carcinogens) (Ecotoxicity)
[65]			(GWP)
[66]	IPCC 2013	Excel	(GWP) (N-R,R) (SWU)
[67]	CML	Gabi	(AP) (EP) (CC)
[68]	IPCC 2013	Umberto	(GWP) (AP) (EP) (CED)

Table 9. *Cont.*

Articles	Method of Impact Assessment	LCIA Software	Impact Category Results
[69]	ReCiPe	SimaPro	(FPMF) (ME) (TEco) (FEco) (MEco) (AP) (POP) (HT) (OLD) (CC) (ALOP) (WDP) (FDP) (IRP) (MDP) (NLT)
[70]	ILCD 2011	EASETECH	(FPMF) (TA) (TE) (FE) (ME) (GWP) (POP) (HT) (OLD) (AD) (CC) (IRP) (Carcinogens) (N-Carcinogens) (Ecotoxicity)
[71]	CML	SimaPro	(GWP) (AP) (EP) (HT) (FDP)
[72]	CML	SimaPro	(GWP) (AP) (POP) (EP) (HT) (OLD) (AD) (FDP)
[73]	TRACI	SimaPro	(GWP) (AP) (EP) (OLD) (FDP) (Smog) (Carcinogens) (N-Carcinogens) (RE)
[4]	ReCiPe	SimaPro	(TA) (FE) (TEco) (FEco) (GWP) (POP) (HT) (RD)
[74]	CML	SimaPro	(GWP) (AP) (POP) (EP) (OLD) (AD)
[75]	CML	SimaPro	(GWP) (AP) (POP) (EP) (HT) (OLD)
[76]	ReCiPe	Gabi	(FPMF) (TA) (FE) (ME) (GWP) (POP) (HT) (OLD) (ALOP) (WDP) (FDP) (IRP) (MDP) (CED)
[77]		Excel	(AP) (EP) (OLD) (RD) (WL) (CC)
[78]	ReCiPe	Gabi	(FPMF) (TA) (TEco) (FEco) (MEco) (GWP) (POP) (EP) (HT) (OLD) (ALOP) (WDP) (FDP) (IRP) (MDP)
[6]	CML	SimaPro	(GWP) (AP) (POP) (EP) (HT) (OLD) (AD)
[79]	CML	SimaPro	(GWP) (AP) (POP) (EP) (OLD) (AD) (FDP) (Ecotoxicity)
[80]	CML	SimaPro	(TEco) (FEco) (MEco) (GWP) (AP) (POP) (HT) (OLD) (AD) (CED) (LU)
[81]	ReCiPe	SimaPro	(GWHH)
[82]	ReCiPe	SimaPro	(GWHH) (FPMF) (HCT) (HN-CT) (TA) (ME) (TEco) (FEco) (MEco)

(GWHH), Global warming Human health; (FPMF), Fine particulate Matter formation; (HCT), Human carcinogenic toxicity; (HN-CT), Human non-carcinogenic toxicity; (GWTE), Global Warming Terrestrial Ecosystems; (GWFE), Global warming Freshwater ecosystems; (TA), Terrestrial Acidification; (TE), Terrestrial Eutrophication; (FE), Freshwater Eutrophication; (ME), Marine Eutrophication; (TEco), Terrestrial Ecotoxicity; (FEco), Freshwater Ecotoxicity; (MEco), Marine Ecotoxicity; (GWP), Global Warming Potential; (AP), Acidification Potential; (POP), Photochemical Oxidation Potential; (EP), Eutrophication Potential; (HT), Human Toxicity; (OLD), Ozone Layer Depletion; (AD), Abiotic Depletion; (RD), Resource Depletion; (WL), Waste Landfill; (CC), Climate Change; (ALOP), Agricultural Land Occupation Potential; (WDP), Water Depletion Potential; (FDP), Fossil Depletion Potential; (IRP), Ionizing Radiation Potential; (MDP), Metal Depletion Potential; (CED), Cumulative Energy Demand; Smog; Carcinogens, (N-Carcinogens), Non-carcinogens; (RE), Respiratory Effects; Ecotoxicity; (NLT), Natural Land Transformation; (ULO), Urban Land Occupation; (N-ReR), Non-Renewable and Renewable; (SWU), Stressed Water Use; (NE), Nutrient Enrichment; (ER), Energy Resources; (NEBR), Net Energy Balance Ratio; (BCR), Benefit Cost Ratio; (LU), Land Use.

The most used method by the articles for Composting LCIA was the CML with a preference of 37%. The other methods addressed were cited with a certain equivalence among them, ranging from 5% to 9% in the frequency of citation. Only one article, Hanandeh [53], used two different characterization methods, CML for the AP, and the ReCiPe category (Midpoint) for the other categories (GWP, ODP, EP, FDP, HTP, IRP and POFP). Almost 20% of the articles did not specify the method, compromising the potential for comparison and replicability.

Over half of the articles (52%) used SimaPro software for LCIA. SimaPro was also used in conjunction with TOTAL software by Kim and Kim [41], for non-existent data cases and avoided products. The software GaBi was the second most cited, used in 9% of the studies. Padeyanda et al. [56] also combined two software packages, STAN and TOTAL, for material flow analysis (MFA) and LCA performance, respectively. Four articles did not specify which software they used.

The ten most cited impact categories are presented in Figure 7. The category GWP was the most used, as it was mentioned 44 times. Additionally, AP, EP, POP and OLD, were addressed in most of the studies.

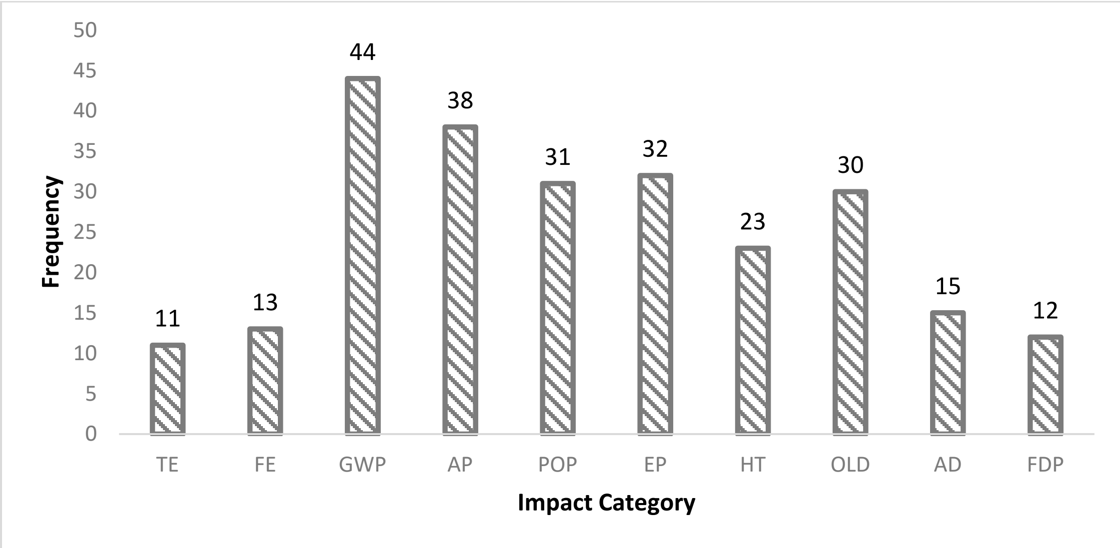

Figure 7. Impact categories that are most cited by the articles for composting process. TE, Terrestrial ecotoxicity; FE, Freshwater Ecotoxicity; GWP, Global Warming Potential; AP, Acidification Potential; (POP), Photochemical Oxidation Potential; (EP), Eutrophication Potential; (HT), Human Toxicity; (OLD), Ozone Layer Depletion; (AD), Abiotic Depletion; (FDP), Fossil Depletion Potential.

The contribution of each impact category is presented in Table 10. Each impact category is quantified using their respective contributors (category indicators) and expressed in a unit of measurement, corresponding to the reference polluting substance [56].

Table 10. Impact Categories and their main contributory processes related to composting.

Impact Categories	Contribution
Global Warming Potential (kg CO_2 eq)	The contribution to the GWP100 category comes from electricity and fuel emissions. The contribution of the composting process can be considered insignificant once the CO_2 produced during the process is considered to come from a biogenic source.
Acidification Potential (kg SO_2 eq)	The main contribution to acidification is produced by process emissions, mainly NH_3, NO_x and SO_x emissions.
Eutrophication Potential (kg $PO_4{}^{3-}$ eq)	The main contributors are from the composting process due to the emission of NH_{4+}, NO_{3-} and $PO_4{}^{3-}$ caused by leaching.
Photochemical Oxidation Potential (kg C_2H_4 eq)	Emissions from the process, namely VOCs emitted during the composting process are the main contributors.
Ozone Layer Depletion (kg CFC–11 eq)	Impacts are derived mainly from energy consumption, represented by fossil fuel consumption.
Human Toxicity (kg 1,4-DB eq)	Fuel and energy consumption are the main contributors to the potential for human toxicity.
Abiotic Depletion (kg Sb eq)	Extraction of non-renewable raw materials is considered, including mineral or fossil substances, such as copper ore and crude oil.
Fossil Depletion Potential (kg oil eq)	The amount of extracted fossil fuel is based on the lower heating value. Diesel consumption for machinery is the main contributor.
Freshwater Ecotoxicity (kg 1,4-DB eq)	Contribution of chemicals emitted into the environment with the potential to cause ecotoxic impacts on aquatic ecosystems leading to damage to the quality of the ecosystem.
Terrestrial Ecotoxicity (kg 1,4-DB eq)	Metals and toxic chemicals released during the treatment process have the potential to cause soil degradation.

Of the different impact categories, 50% (Global Warming Potential, Ozone Layer Depletion, Human Toxicity, Abiotic Depletion and Fossil Depletion Potential) were mostly associated with emissions from the consumption of fossil fuels and electricity. Processes that consume high-energy content materials tend to have a higher value in these categories.

4.6. Results and Their Interpretation

In the interpretation stage of the LCA, results are discussed as support for the conclusions and to provide relevant indications for decision-making in accordance with the defined goal and scope of the study.

Thirteen articles were found that used the CML impact assessment method and the same functional unit for the 10 most cited impact categories in the 56 articles in this review (Table 11).

The ANOVA results show that there was a significant difference ($p < 0.05$) in the impact categories AP [F (6, 11) = 6.139, p = 0.000], POP [F (6, 5) = 63.413, p = 0.000], and ADP [F (6, 3) = 26.449, p = 0.011].

The GWP and EP (Figure 8a–c) impact categories had the highest values for Composting (Non-Specified) operation mode. However, these categories showed a high degree of data variability. Data variability within the same composting method can be explained by the heterogeneity of flows (inputs and outputs) that the authors included within the system boundaries. As an example, Lee et al. [33] obtained high CO_2 eq (270 kg CO_2 eq/t) because they estimated a high value for CO_2 (210 kg/t) emitted directly from the composting of food waste. Meanwhile, Oldfield et al. [57] obtained the lowest value for CO_2 eq (79 kg CO2 eq/t) because they considered the compost as an organic fertilizer and NPK avoidance at the system boundary.

Table 11. Results of the most cited impact categories, regarding the CML impact assessment method and functional unit of one t of organic waste.

Articles	Operation Mode	TE	FE	GWP	AP	EP	POP	HT	OLD	ADP	FDP
		kg 1,4-DB eq/fu	kg 1,4-DB eq/fu	kg CO_2 eq/fu	kg SO_2 eq/fu	kg PO_4^{3-} eq/fu	kg C_2H_4 eq/fu	kg 1,4-DB eq/fu	kg CFC-11 eq/fu	kg Sb eq/fu	kg oil eq/fu
Lee et al. (2007) [33]	C*		0.82	270	1.29	0.23		13			
Padeyanda et al. (2016) [56]	C*			130.37	0.29	7.14	0.02				
Oldfield et al. (2016) [57]	C*			79	1.58	3.5E-01					
Shih et al. (2021) [80]	C*	0.31	13.04	103	0.58	0.18	1.85×10^{-2}	23.42	7.92×10^{-6}	0.72	
Colón et al. (2010) [38]	HC			82.6	0.126	0.0155	0.14		2.44×10^{-6}	0.192	
Colón et al. (2012) [48]	HC			209	1.4	0.297	0.233	1.94	3.05×10^{-7}	0.0411	
Abeliotis et al. (2016) [55]	HC	0.0154	3.22×10^{-3}	151.5	0.16	0.029	3.17×10^{-3}	0.0444			
Lu et al. (2020) [71]	HC			62.7	0.89	0.664		6.01			13.2
Lu et al. (2020) [71]	HC			56.7	0.88	0.661		5.05			10.7
Martínez-Blanco et al. (2010) [39]	IC			153	0.777	0.223	0.535		1.33×10^{-5}	0.768	
Mondello et al. (2017) [62]	IC	0.2	12.26	99.28	0.5	0.11	1.79×10^{-2}	20.82	7.75×10^{-6}	0.65	
Colón et al. (2012) [48]	IV			150	1.3	0.094	0.192	23.5	7.12×10^{-6}	0.872	
Lu et al. (2020) [71]	IV			97	0.91	0.42		40.7			42.3
Colón et al. (2012) [48]	TWC			196	14	3.03	2.38	5.82	2.37×10^{-6}	0.144	
Colón et al. (2015) [54]	TWC			196	14	3.03	2.38		2.37×10^{-6}	0.14	
Lu et al. (2020) [71]	WC			67.1	0.82	0.35		38			33.5
Al-Rumaihi et al. (2020) [72]	WC			128							
Colón et al. (2012) [48]	WC			123	3.75	0.721	2.59	11.7	5.42×10^{-6}	0.434	
Ng et al. (2021) [6]	PASP			126	0.95	1.39	0.0156	3.3	0.0000121	9.54×10^{-6}	

TE, Terrestrial Ecotoxicity; FE, Freshwater Ecotoxicity; GWP, Global Warming Potential; AP, Acidification Potential; EP, Eutrophication Potential; POP, Photochemical Oxidation; HT, Human Toxicity; OLD, Ozone Layer Depletion; AD, Abiotic Depletion; FDP, Fossil Depletion Potential. C*, Composting (Not Specified); HC, Home Composting; IC, Industrial Composting; IV, In-vessel Composting; TWC, Turned Windrow Composting; WC, Windrow Composting; PASP, Passive-aerated Static Pile.

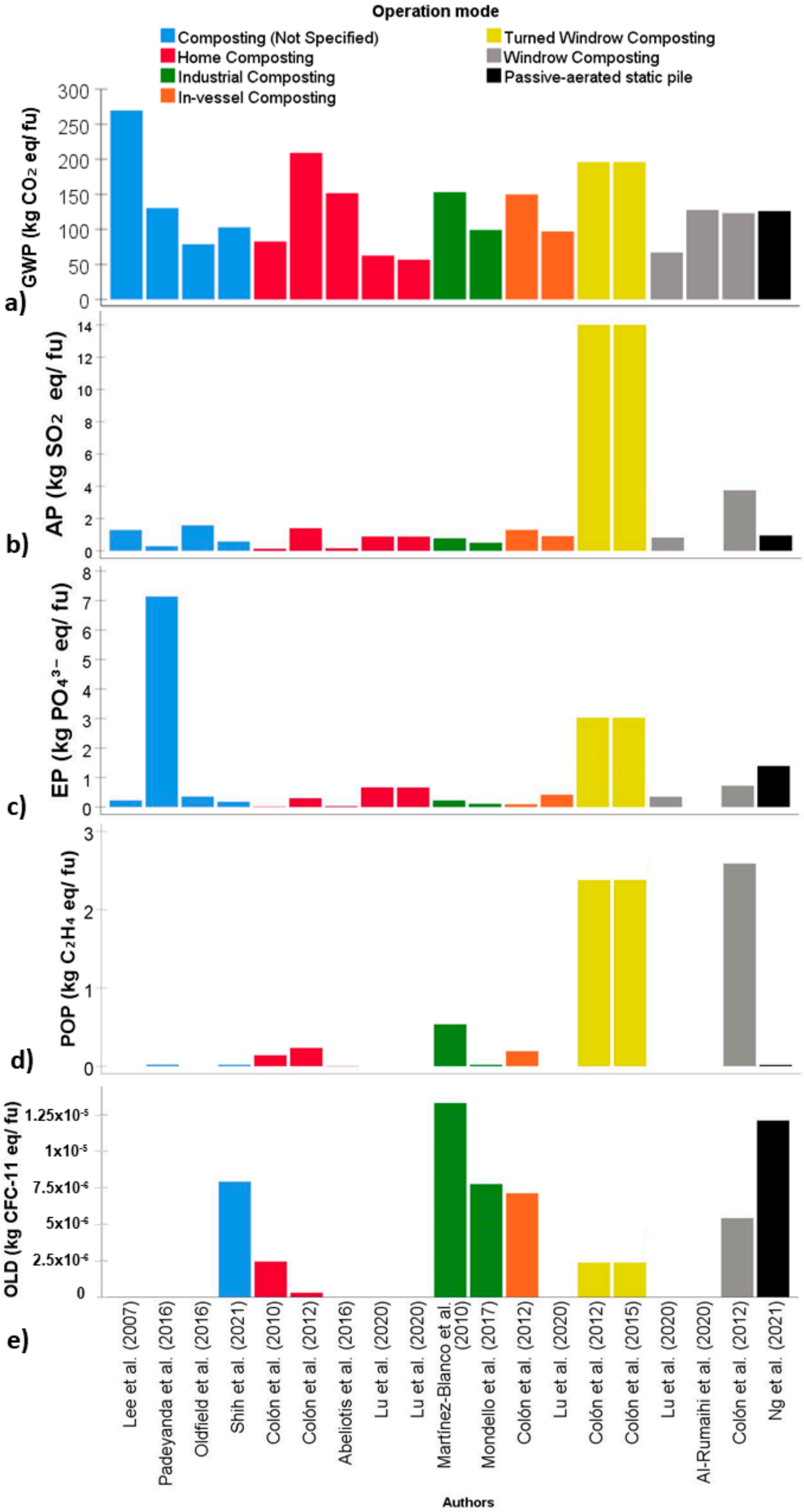

Figure 8. Absolute data for the impact metrics by the composting operation mode for the five most cited impact categories GWP, AP, EP, POP and OLD.5. Synthesis of LCA in Composting Process.

Padeyanda et al. [56] found a very high EP value for Composting (Not Specified), more than 7 kg PO_4^{3-} eq/t of food waste, due to the high NH_3 emission during the composting process. The eutrophication category is more affected by excess nutrients derived from nitrogen and phosphorus, that in high concentrations in organic waste to be composted, can affect the ecosystem with eutrophication [88]. Another aspect that can increase the EP results is considering the high concentration of nutrients from the wastewater generated on composting piles and often leachate into the soil [33].

For the AP and POP (Figure 8b–d) categories, the highest values were found in Turned Windrow Composting, which may be due to the high ammonia and VOC emissions from the process and from the use of fossil fuel in turning the windrows. The POP category also had the highest value for the Windrow Composting mode, however, only one study was found using this method and impact [48]. For the OLD category, the highest value was found in Industrial Composting and Passive-aerated Static Piles, mainly due to the high consumption of fossil fuels and electricity required for large-scale plants operation, use of extra auxiliary materials (equipment), use of energy for material preparation (shredding), and gas emissions from composting process [6,39].

Colón et al. [48,54] obtained high values for the Turned Windrow Composting mode, as the plant emitted large amounts of NH_3 and VOC, as it did not include an exhaust gas emission treatment process, such as biofilter equipment [81]. Other emissions such as NO_x, SO_x and PM, generated during the operation of the windrow-turned equipment and other vehicles operating during windrow turns, are responsible for Terrestrial Acidification and Particulate Matter Formation [89]. Ammonia emission has a significant contribution as an air pollutant to the Acidification and Eutrophication impact categories and is possibly the reason for the loss of nitrogen in the final compost [48].

Overall, despite the heterogeneity in LCA approaches, results suggest that In-vessel Composting and Home Composting had the lowest impact in all categories, indicating that they are the best environmental options among composting methods. Generally, aerobic composting operated in closed areas has better control because it can include systems that collect and treat the gases [48]. In the case of Home Composting, it avoids the stages of collection and transport of waste, reducing energy and infrastructure requirements, and requires less land use, while prompting a sustainable local use of the compost, if performed under the appropriate conditions [38].

The results (Figure 8) also demonstrate the particularities of each composting method, indicating that not all impact categories simultaneously expressed the highest values for the same method. Composting (Unspecified) was the only method that contributed to the highest values, simultaneously, in two categories of impacts: GWP and EP. Due to the diverse operational needs of each composting method, there are meaningful differences in the number of flows that are generated and contribute to the impact category. As an example, if a composting method uses more fossil fuels and therefore emits more GHGs, it will have a higher GWP. Such results provide useful information for decision-making, as it allows for the recognition of the most impactful stages and processes.

5. Synthesis of LCA in Composting Process

5.1. Sources Contributing to Impact Results

The systematic analysis of the 56 articles showed that gaseous emissions from the composting process represent the main contribution to the potential of Global Warming, Acidification, Eutrophication, Photochemical Oxidation and Human Toxicity [21,51,75]. The largest contributions came from the emissions of CH_4, N_2O and NH_3 resulting from the decomposition process [49,50].

In the study by Thuppahige et al. [81], the highest environmental load was caused by the composting process and the consumption of electricity, water and diesel. Gaseous emissions CH_4, N_2O, and NH_3, besides directly affecting the categories Global Warming and Terrestrial Acidification, N_2O and NH_3 were responsible for also affect the Stratospheric Ozone Layer Depletion, and Fine Particulate Matter formation (FPMF), respectively

Zhao et al. [51] argued that food waste composting causes acidification and enrichment of nutrients more severely than landfills due to NH_3 and SO_2 emissions during decomposition. This contribution to Acidification Potential, Terrestrial and Marine Eutrophication is mainly caused by ammonia emissions that occur during decomposition, in the solubilization of nitrogen [61]. Despite these results, composting has downstream benefits when applied to the soil, which is often neglected in LCA.

When composting plants are poorly managed, low turning frequency and non-uniform aeration can emit GHG emissions (CH_4 and N_2O), contributing to GWP [42,47]. Another process responsible for the aggravating GWP results is the use of machines that use fuel and electricity from fossil sources, due to the emissions of CO_2 [6]. In Cadena et al. [21], the use of fuel and electricity represented the highest contribution to the Global Warming Potential, Photochemical Oxidation, Human Toxicity and Ozone Layer Depletion due to the CO_2 derived from fossils, VOCs and fossil consumption [56]. On the other hand, the consumption of diesel by the machines affected the categories associated with fossil resource depletion from the combustion of fuels [48,50,81].

The use of compost as an organic fertilizer generated some environmental burdens related to air emissions and diesel consumption during the application stage, associated with the use of machinery [4]. Excessive fertilization (high N input to the soil) contributes to nutrient enrichment and nitrogen loss through NO_{3-} release from the soil into groundwater [90]. However, the use of compost on agricultural land only marginally reduces the impacts on Global Warming, Acidification, Ecotoxicity and Human Toxicity by replacing N, P and K fertilizers [51].

When analysing the composter manufacturing and tools (garden chipper, bag collection, shovel, mixing tool, watering can and gloves) for the composting operation, the study of Colon et al. [38] found the composter was the main contributor to the total environmental impact of the domestic composting process for the categories of the impact of Abiotic Depletion, Ozone Layer Depletion, and Cumulative Energy Demand (CED) [38]. Among the operations of the composting chain, the construction of the plant (especially the concrete building) consumed a large amount of electricity and fuel, which from an environmental point of view are the most impacting items [65].

5.2. Comparing Composting Techniques and other Solid Waste Treatment Techniques

Overall, experimental composting systems reduce the environmental impact in all categories analysed to a greater percentage than the worst option (mineral fertilizer or industrial compost), except for the categories Ozone Layer Depletion Potential and Acidification Potential [36].

Composting plants when compared with Home Composting, had one of the smallest impacts on Climate Change and Ozone Layer Depletion, but had considerable environmental impacts on Particulate Matter Formation and Freshwater Ecotoxicity [58]. Home Composting has the greatest potential for reducing CO_2 eq emissions, when compared with Composting Plants, however, it is important to pay attention to the high emission of N_2O. For Home Composting, the composter manufacturing and the gaseous emissions from the composting process are the main impacts, while for Industrial Composting, the main contributions come from the collection and transport of organic waste, consumption of electricity, waste disposal and emission of COVs [39]. As presented in Oliveira et al. [58], in comparison with Composting Plants, Household Composting had lower CO_2 eq emissions and higher N_2O emissions, which may be due to a lack of temperature control.

Another study [71] showed that Domestic Composting when performed in a large capacity composter has the best overall performance, followed by composting in centralized windrows. Energy Consumption was the greatest environmental impact when considering the processes of waste collection and transportation. While in the domestic composting system the emissions released from waste degradation were the most harmful impact, followed by the manufacture of dumpsters. In Andersen et al. [47], Domestic Composting performed better, as did incineration and landfilling in various impact categories (especially in terms of NE, AC and ETw).

In Boldrin et al. [46], Tunnel Composting performed better than Windrow Composting, in the categories of Global Warming, Acidification and Nutrient Enrichment, due to lower electricity consumption and lower CO_2 fossil, CH_4, N_2O and NH_3 emissions. A study by Kim and Kim [41] compared treatment technologies and found that the landfill had the higher GHG emissions (kg CO_2 eq/FU), followed by dry feeding, composting and wet feeding. However, the study by Kong et al. [2] argued that landfilling appeared to be better or at least equivalent to composting or anaerobic digestion to reduce GHG emissions, but was worse for the impacts associated with Resource Conservation and Land Use. Landfilling, when well-managed, can remarkably reduce GHG emissions when compared to composting and anaerobic digestion. However, Composting and Anaerobic Digestion are particularly important for the diversion of organic waste from the landfill, complementing each other rather than replacing the landfill. In-vessel Composting compared to landfill, has lower GHG emissions and Eutrophication [59].

The analysis of Mondello et al. [62] compared scenarios between composting, landfill, incineration, anaerobic digestion and bioconversion with *Hermetia illucens* (Black Soldier Fly). The composting scenario had lower contributions to environmental impacts than landfill and incineration scenarios, and higher contributions than the anaerobic digestion and *H. illucens* scenarios in analysed impact categories (ADP, AP, EP, GWP, OLD, HT, FWAE, MAE, TE, POP, Energy Use and Land Use). Concerning GWP, the greatest impacts are due to electricity consumption during the treatment phase, contributing to 51.9% [62].

Gao et al. [63] compared three environmental impacts categories (Climate Change, Acidification/Eutrophication and Carcinogens) for the treatment of food waste with five different methods: anaerobic digestion, landfill, incineration, composting and heat-moisture reaction. For the impact of Climate Change, anaerobic digestion had the lowest impact, followed by composting. For the Acidification/Eutrophication impact, Composting had the third lowest contribution, behind anaerobic digestion and Heat-moisture reaction. For Carcinogens, Composting had the lowest results while Incineration had the highest contribution. In the treatment of kitchen waste, Shih et al. [80] found that when comparing incineration, landfilling, composting and anaerobic digestion, the last process can bring more benefits with the lowest potential environmental impacts and high energy recovery performance. However, Composting, as an aerobic process, is a more popular process than anaerobic digestion, as it is more suitable for application on a larger scale, while not requiring inoculating bran, which is a limiting factor in anaerobic digestion [73].

When compared to Windrow Composting, the combination of Composting and Anaerobic Digestion had relevant negative environmental loads in Abiotic Depletion (with fossil fuels), GWP and OLD [76]. Most of the emissions generated are due to the use of fossil fuels during transportation, which corresponds to approximately 60% of the total impact of the Global Warming Potential, and 40% is due to the composting process itself. The study by Mancini et al. [69] also stated that the integration of Anaerobic Digestion with Composting can perform better environmentally when compared to the single composting solution. The significant reduction of GWP impacts by Anaerobic Digestion with Composting can be due to energy recovery from biogas by Anaerobic Digestion, reduction of energy requirement by both processes (Anaerobic Digestion and Composting) and CO_2 sequestration by the compost produced after digestion of the material [91].

5.3. Adopting Mitigation Measures by the Articles

The most important factors that may positively influence the emission of methane (CH_4), nitrous oxide (N_2O) and ammonia (NH_3) during composting are the composition of the source feedstock (C/N ratio), aeration, temperature, pH and size and design of the pile [92]. Increasing air flow with ventilation and collecting and treating the gases before release into the atmosphere will reduce their pollution loads.

To reduce NH_3 emission, monitoring the temperature of the windrows and inducing the venting of the system should be considered, because high temperatures decrease the nitrification of NH_4^+, favouring the evaporation of NH3 [42,92,93]. It is important to reduce

NH_3 during the initial phase of decomposition or to eliminate it by collecting it in a biofilter and an acid wash system [34].

As the collection of organic wastes and treatment steps are the main contributors to a higher GWP impact on the environment due to the use of energy from fuels [64], the use of more efficient equipment is recommended to achieve reductions in fuel consumption and air emissions [81]. Impact values can also be reduced by implementing efficient gaseous emission treatments and by changing the energy source for renewable technologies [21].

Anaerobic digestion, coupled with the use of biogas for energy production, has negative environmental loads in the impacts of Climate Change and Fossil Fuel Depletion, as they manage to generate energy in the form of electricity and heat and compensate in their operations while composting does not include the energy generation. The phase that most contributes to Climate Change and Fossil Fuel Depletion in composting is the collection and transport of waste, which can be reduced if the energetic grid mix change for renewable energy, in this way composting gains an advantage over incineration and anaerobic digestion [64,76]. Therefore, the decarbonization of the national grid and increased efficiency in using natural and energy resources are necessary to achieve sustainable production and promote a circular economy [76,94].

The finished compound that is produced in the composting plant should have the necessary quality to be used in parks and gardens, in agriculture or as a substitute for peat in plant growth [42]. Greenhouse emissions are partially offset by avoided fertilizers, virgin raw materials avoided and carbon dioxide sequestration. Emissions from the compost produced are also the dominant contributors to the acidification and eutrophication categories but are compensated by the impacts avoided due to the replacement of synthetic NPK fertilizers [35].

Replacing disposal (in landfill) with composting, and replacing chemical fertilizers with compost, greatly reduces environmental impacts, especially Ecotoxicity, Non-Carcinogenic, Carcinogenic, Eutrophication, and Global Warming (46.0%, 22.7%, 22.2%, 20.9%, and 9.7%, respectively) [73]. This reduction is due to the avoided use of fossil fuel used to excavate and move the soil to build a sanitary landfill and the avoided manufacture of synthetic fertilizers substituted for the compost produced by composting [39].

The overall environmental loads can also be reduced by separating food waste at the source and treating it by anaerobic digestion and then composting the resulting digestate [60]. The selection of the type of bulking agent added in the composting formulation also is very important because it can reduce and even prevent leachate and GHG emissions [16]. Fortunately, the best bulky agents may be available locally and are readily available from agricultural waste such as sawdust, wood chips, cornstalks, mushrooms and cotton, also solving the disposal of this waste [1].

6. Conclusions

This study reviewed 56 studies using LCA to assess the environmental impacts of the composting process. This process provided critical information on the potential environmental impact of the multiple solid organic waste management options, supporting decision-making.

The existent LCA knowledge suggests that Composting is a valuable option for the treatment of solid organic waste when considering its environmental impacts. The LCA studies suggest that the main contributing factors to the GWP and AP impact categories were the emissions of CH_4, N_2O, and NH_3, formed in the biological composting process, and are particularly high when composting plants are poorly managed with low turning frequency and non-uniform aeration. Moreover, the lack of in situ measurements of gaseous pollutants make mitigation measures difficult and reduces the efficient removal of these gases. Furthermore, the lack of measurements increases the uncertainty of LCA results and may underestimate or overestimate results.

The studies that compared composting with other treatment technologies indicated that the composting process had a greater contribution to the GWP, NE, and ETw impact categories. The combination of composting and anaerobic digestion should provide better efficiency, reducing waste management impacts than composting alone, mainly in the Abiotic Depletion (with fossil fuels), GWP, and OLD impacts. Composting and anaerobic digestion are very important for the diversion of organic waste from landfill, complementing each other rather than replacing landfills. When comparing different composting methods, using the predominant method (CML) the statistical analysis indicated that In-vessel Composting and Home Composting had lower environmental impact estimates. However, such results were influenced by the heterogeneity within the different system boundaries.

Like any other industrial production chain, composting uses substantial amounts of electricity and fossil fuel for its operation and transportation of materials. Approximately 60% of the total Global Warming Potential impact is due to emissions generated from the use of fossil fuels during transport. The energy consumption for operation and transport still depends heavily on the adopted energetic grid mix, which in many countries still relies on non-renewable sources such as petroleum, coal, or natural gas. Therefore, the transition to renewable energy would increase the advantages of composting over other technologies (e.g., Incineration with energy production or Landfilling).

While composting techniques need to be considered and encouraged by public and private managers, many adjustments can be performed and are still needed. Additional LCA studies are necessary, covering different organic wastes and composting techniques to improve the environmental impacts and the long-term benefits of composting, for a cleaner technique.

Despite the valuable contribution of the LCA studies, the great diversity among both methodological definitions, such as the functional units and the product system boundaries, and environmental impact assessment definitions, such as environmental impact categories, make the comparison between studies particularly complex. Moreover, most LCA studies were based on limited inventory primary data, thus generating less accurate results, which may lead to misinterpretations and ambiguities. These are indeed major limitations and demand for an increase in uniformity and data consistency in LCA processes.

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