

# Life cycle assessment of municipal biowaste management services: a comprehensive literature review of trends, methods and good practices

Roberta Salomone, Alice Mondello, Dinh Linh Le,  
Giovanni Mondello, Giuseppe Saija, Francesco Lanuzza and  
Daniela Baglieri

*Department of Economics, University of Messina, Messina, Italy*

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## Abstract

**Purpose** – Municipal biowaste is the primary component of global municipal solid waste and can lead to significant environmental impacts. Life cycle assessment (LCA) is increasingly used to evaluate various waste management services and practices, but certain challenges may arise due to the diversity of practices and methodological choices for applying the method. While numerous review articles address LCAs for waste management, most present notable limitations. Therefore, this study aims to provide an in-depth examination of the literature in this field to accurately investigate trends, methods and good practices.

**Design/methodology/approach** – This study examines 308 peer-reviewed articles collected from the Scopus and Web of Science databases, analysed through bibliometric, systematic and content analysis methods.

**Findings** – Results show an increasing interest in the topic over the last decade, with anaerobic digestion and composting emerging as the most commonly assessed approaches. Their combination has been identified as a good practice due to the associated environmental benefits. However, the analysis also highlights that environmental performance is strongly context-dependent, being influenced by factors such as system scale, logistics and waste composition. Finally, results highlight a predominant use of mass-based functional units and varying system boundaries, with the climate change impact category most frequently assessed.

**Originality/value** – This study enhances understanding of LCA applications to biowaste management systems and services, offering methodological guidance for future research and practice supporting the design of sustainable waste management services within local circular economy frameworks. Its originality lies in providing a service-oriented perspective that identifies methodological patterns and context-dependent good practices, while also strengthening the decision-making relevance of LCAs for

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municipal biowaste management and highlighting key areas for improving their comparability and reliability.

**Keywords** Environmental sustainability, LCA, Municipal biowaste, Organic fraction, Systematic review, Waste treatment

**Paper type** Literature review

## 1. Introduction

Municipal biowaste is the largest component of municipal solid waste (MSW) (Arfelli *et al.*, 2023), projected to globally reach nearly 3.8 billion metric tons annually by 2050 (Statista, 2024). Biowaste refers to the organic fraction of MSW, defined as “biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises, and comparable waste from food processing plants” (European Commission, 2008). If not properly managed, biowaste management services and systems can lead to significant environmental impacts, particularly related to climate change (Aleisa and Alsaleh, 2024; Iqbal *et al.*, 2020). The United Nations Environment Programme (UNEP) reports that food waste alone accounts for 8%–10% of global greenhouse gas (GHG) emissions (UNEP, 2024), while landfilling and incineration of biowaste generate an additional 3%–5% (Iqbal *et al.*, 2020). Therefore, identifying effective management services and practices is essential to mitigate these impacts.

Several strategies for biowaste management services and practices are discussed in the literature, ranging from conventional disposal (e.g. open dumping, landfilling) (Cheela *et al.*, 2021; Xiao *et al.*, 2023) to valorisation options such as composting, anaerobic digestion (AD), waste-to-energy and insect-based bioconversion (Arfelli *et al.*, 2023; Brancoli *et al.*, 2020; Salomone *et al.*, 2017). However, each alternative entails trade-offs in terms of emissions, resource recovery and energy use. Life cycle assessment (LCA) provides a systematic framework to quantify these trade-offs by evaluating environmental impacts across all life cycle stages (ISO, 2006a, 2006b). Despite its extensive application, the diversity of treatment technologies, service configurations and methodological choices complicates the comparison and interpretation of results.

Existing review studies have addressed LCA applications in waste management from different angles, including critical discussions of LCA modelling assumptions (Gentil *et al.*, 2010), worldwide assessments of LCA use in MSW management (Khandelwal *et al.*, 2019), and reviews of integrated MSW management in specific regional contexts (Othman *et al.*, 2013). However, most are limited by small or unsystematic samples and tend to focus on treatment technologies or broad MSW systems, with limited attention to how municipal service configurations (e.g. collection organisation, scale) shape LCA modelling choices and the interpretation of results. A recent review has analysed LCA studies related to food waste management technologies (Batool *et al.*, 2024). Despite this, biowaste is not limited to food waste, since it refers to a broader category of biodegradable waste, and its management service structures and operational models may differ (Alves *et al.*, 2024).

Consequently, a systematic and comprehensive synthesis of LCA applications specifically addressing municipal biowaste management services and systems is still missing. In this review, management services are analysed in terms of how biowaste treatment technologies are organised at the municipal level (e.g. collection and logistics organisation, system scale, centralised versus decentralised schemes), and how these configurations are associated with recurring LCA methodological choices (e.g. functional units [FUs], system boundaries [SBs] and multi-functionality management), an aspect largely overlooked in technology-centred LCA reviews.

In this context, this study employs a combination of bibliometric, content, and systematic literature review to:

- 
- map the state of the art in research on LCA for biowaste management;
  - synthesize current approaches and identify good practices in biowaste management services; and
  - examine methodological patterns to inform the design of future LCAs in this field.

This integration enables a cross-reading of bibliometric trends, content-based findings and LCA methodological patterns, supporting a more coherent interpretation of the reviewed evidence. In this context, “good practices” are identified by interpreting the environmental performance reported in the reviewed LCA studies, considering the methodological choices adopted.

These objectives directly reflect the research questions guiding this review and the investigated articles (see section 2. Materials and methods, and [Figure 1](#)), which address:

- the state of the art and its evolution over time;
- current approaches and good practices; and
- the main methodological issues in LCAs of municipal biowaste management.

This study is conducted within the scope of the project “Reducing Emissions through Waste Practices and new business models – Measuring Effects” (REWARD-ME), part of the extended research partnership GRINS-Growing Resilient, Inclusive and Sustainable. Although the project focuses on sustainable waste management practices and community composting, the review independently analyses the international LCA literature on municipal biowaste, including studies that model organic fractions within broader MSW systems to ensure comprehensive coverage.

## 2. Materials and methods

This study employs a mixed-methods approach, combining bibliometric ([Wallin, 2005](#)), systematic ([Khan et al., 2003](#)) and content ([Gaur and Kumar, 2018](#)) analyses to provide both quantitative and qualitative insights into the LCA literature on biowaste management. The integration of these methods allows mapping research trends, identifying current approaches and good practices, and analysing key methodological aspects of LCA applications, while enabling a cross-reading of the different analytical levels and supporting a more coherent interpretation of results.

To ensure transparency and reproducibility, this study follows the Framework for systematic Literature review to Analyse Vast Information in Life Cycle Thinking studies (FLAVIA-LCT) developed by [Gulotta et al. \(2023\)](#), which is applied with particular attention to operational and service-related aspects relevant to municipal biowaste management. The WOMEN components, as defined by [Gulotta et al. \(2023\)](#) – W: Who, What, When, Where, Which, Whom, Why and how; O: Object of the study; M: LCT Method to be investigated; E: Evidence of Effect the review wants to evaluate; N: Network of interest – were used to define the research question and guide data collection ([Figure 1](#)).

Scientific articles were retrieved from the Scopus (SP) and Web of Science (WoS) databases using a search query based on the EU definition of biowaste ([European Commission, 2008](#)) to ensure that all papers concerning LCA for biowaste management are identified.

The literature search and screening ([Table 1](#)) were conducted in two rounds (November 2024 and May 2025) without time restrictions. Duplicates and non-English, non-journal or review papers were excluded, as well as studies not addressing biowaste or not applying the LCA method. After full-text screening, 308 peer-reviewed articles were retained.

This systematic screening ensures a comprehensive and representative data set of international LCA applications for biowaste management.

Data extraction is carried out by collecting three main types of information:

## FLAVIA-LCT flow diagram

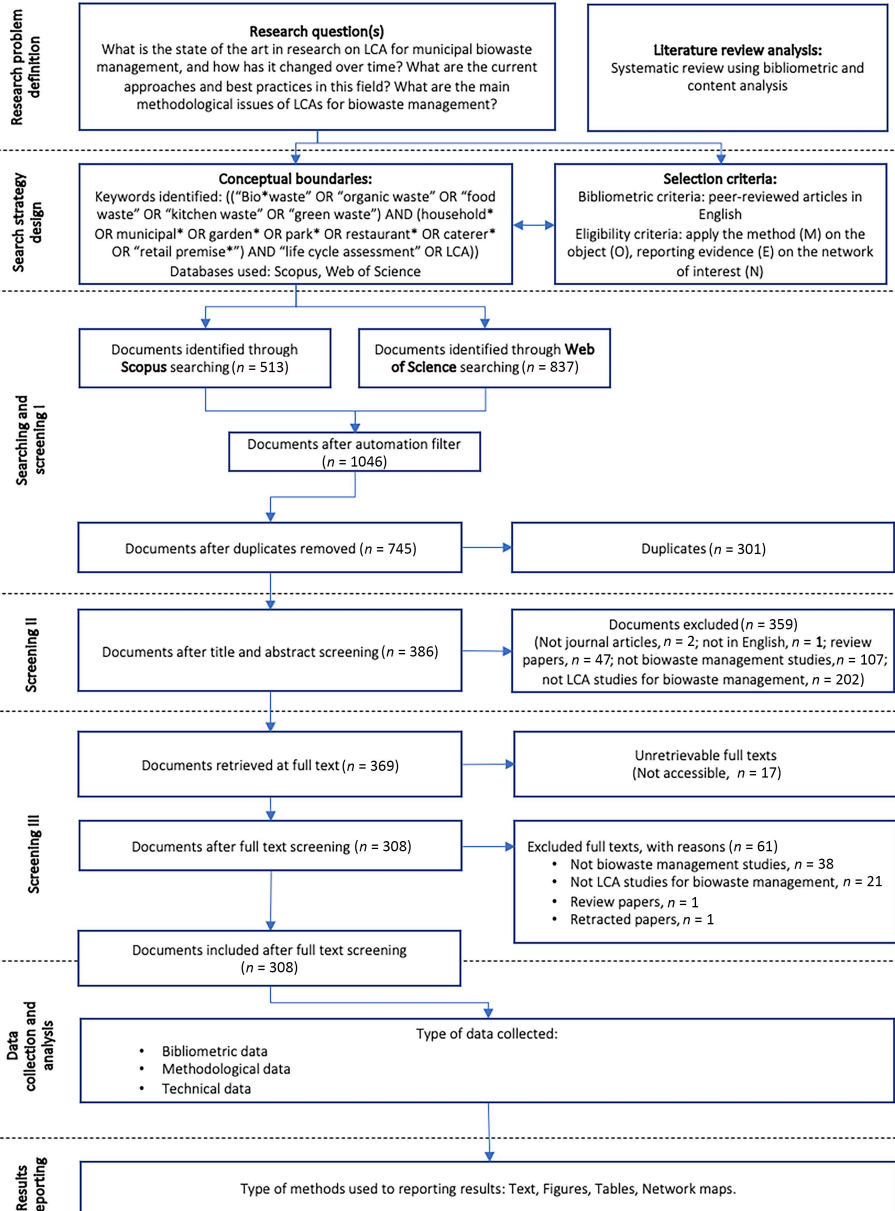


Figure 1. FLAVIA-LCT flow diagram

Source: [Gulotta et al., 2023](#)

**Table 1.** Summary of literature search and screening

Step	Criteria applied	Excluded (n)	Remaining (n)
Initial search (11/11/2024)	All records retrieved		1,274
Language/type filtering	Non-English, non-journals, reviews	566	708
Title/abstract screening	Not relevant to LCA or biowaste	347	361
Full-text eligibility	Not LCA/biowaste or inaccessible	72	289
Update (29/05/2025)	Additional records included		+19
Final sample			308

(i) Bibliometric data – authors, year, journal, keywords and country affiliations. These data were processed using VOSviewer (van Eck and Waltman, 2010) for keywords networks, Biblioshiny R (Bibliometrix, 2025) for geographical mapping, and Microsoft Excel for yearly and source distributions.

(ii) Technical data – information on biowaste types, management methods and environmental performance indicators. These were compiled through content analysis, allowing the identification of current approaches and good practices.

(iii) Methodological data – information on LCA modelling choices. To enhance the comparability of the reviewed studies, the systematic analysis of this data was based on the FLAVIA-LCT framework (Gulotta *et al.*, 2023), mapping methodological patterns across the four LCA phases (goal and scope definition, inventory analysis, impact assessment, interpretation). Within each phase, key methodological elements were identified and used to classify the studies, including FU, SBs and multi-functionality management (goal and scope), data sources and modelling approach (inventory analysis), impact assessment methods and categories (impact assessment), and the presence of sensitivity and uncertainty analyses (interpretation).

Investigator triangulation is performed to ensure a higher quality of the analysis (Adams *et al.*, 2015). Two authors independently analysed the studies, and any discrepancies were resolved through discussion and final review by the other co-authors involved in the study.

### 3. Results

The results of this study are presented in three macro categories:

- (1) bibliometric analysis;
- (2) biowaste management – current approaches and good practices; and
- (3) methodological choices of LCAs for biowaste management.

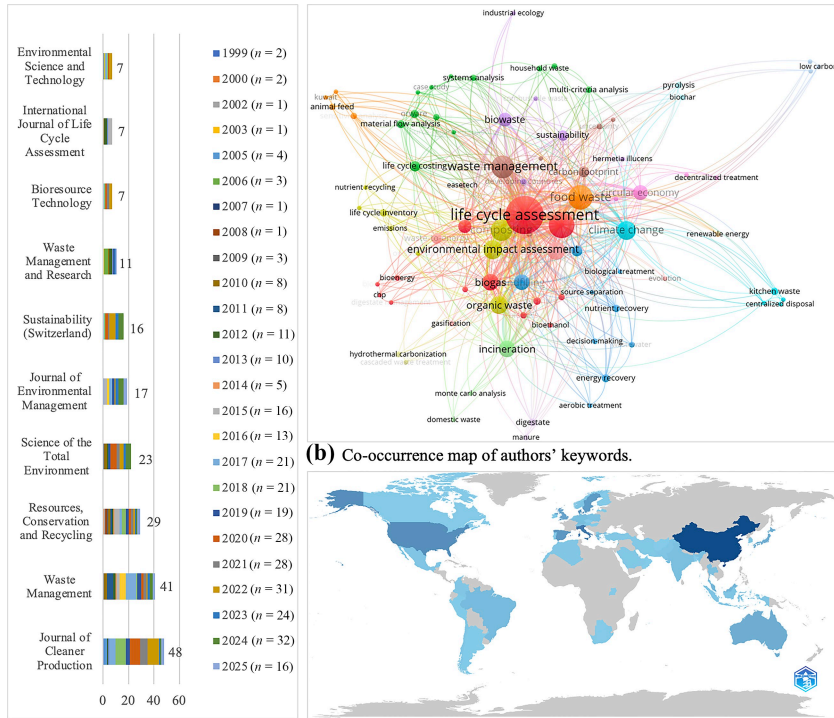
Relevant subsections are organised to disseminate the findings accordingly.

#### 3.1 Bibliometric analysis

The bibliometric analysis focuses on four key aspects:

- (1) year of publications;
- (2) journal sources;
- (3) authors' keywords; and
- (4) country of publications (see Supplementary Materials, Table S1).

The main results are depicted in Figure 2.



**Figure 2.** Main bibliometric results for a) year of publication and journal source; b) authors' keywords; c) country of publication  
**Source:** Authors' own work

A total of 308 peer-reviewed articles, published between 1999 and May 2025, were analysed. The number of publications has steadily increased over time, particularly after 2015, reflecting the growing relevance of biowaste management in environmental policy and circular economy research. The year 2024 recorded the highest number of publications ( $n = 32$ ); however, 2025 only accounted for publications up to May ( $n = 15$ ).

Papers were distributed across 69 journals, but only a few account for more than half of the total sample [Figure 2(a)]. The Journal of Cleaner Production ( $n = 48$ ) and Waste Management ( $n = 41$ ) dominated the field, followed by Resources, Conservation and Recycling ( $n = 29$ ), Science of the Total Environment ( $n = 23$ ) and Journal of Environmental Management ( $n = 17$ ). These journals play a central role in disseminating LCA research on waste management.

Keyword co-occurrence mapping [Figure 2(b)] represents 162 author keywords with at least two occurrences, which are then reduced to 85 after applying the thesaurus file (see Supplementary Materials, Table S2). The map reveals a strong cluster centred on "life cycle assessment" ( $n = 224$ ), "anaerobic digestion" ( $n = 89$ ) and "food waste", highlighting the methodological and thematic focus of the sample. Other recurrent terms include "waste management" ( $n = 69$ ), "composting" ( $n = 61$ ) and "climate change" ( $n = 45$ ). These indicate that "anaerobic digestion" and "composting"

are the most frequently assessed technologies, while climate-related impact categories are the most evaluated in the sample.

Regarding the geographical distribution, [Figure 2\(c\)](#) shows a marked concentration of publications in China (224 publications) and Europe, especially Italy ( $n=139$ ), Denmark ( $n=99$ ), Spain ( $n=87$ ) and Sweden ( $n=82$ ). This distribution mirrors global waste management priorities: industrialised nations explore optimisation of existing systems (e.g. [ISPRA, 2023](#)), while China's strong output reflects its rapid policy transition towards sustainable MSW treatment ([Statista, 2025](#)).

### 3.2 Biowaste management – current approaches and good practices

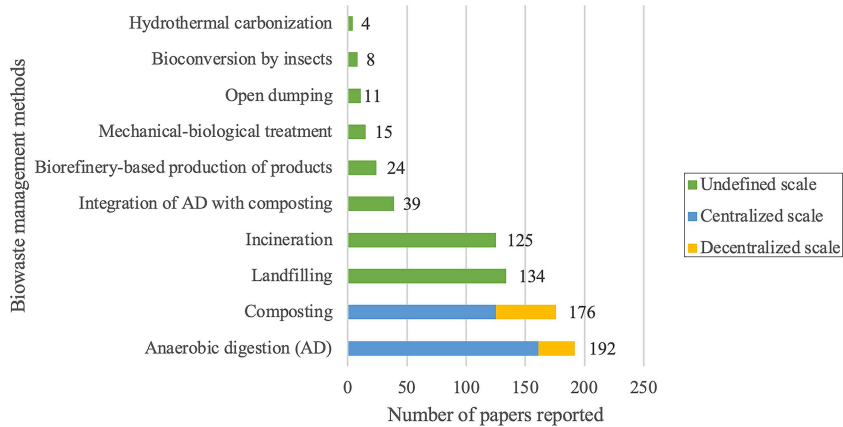
The reviewed studies address a wide range of biowaste management services and methods, from conventional disposal to advanced recovery systems. Ten main categories were identified, with AD and composting emerging as the most investigated and environmentally favourable service-based approaches.

[Table 2](#) and [Figure 3](#) summarise the main options, their frequency of occurrence in the sample, and their typical outputs.

**3.2.1 Anaerobic digestion and composting.** AD and composting emerge as the most commonly assessed approaches for biowaste management services. As reported in [Figure 3](#), both centralised (light blue) and decentralised (yellow) options of AD ( $n=161$ ;  $n=31$ ) and composting ( $n=125$ ;  $n=51$ ) are examined. Centralised facilities treat large volumes of waste efficiently, while

**Table 2.** Overview of biowaste management methods in reviewed LCA studies

Method	Description/ typical configuration	Main outputs	No. of studies	References (examples)
Anaerobic digestion (AD)	Centralised or decentralised; wet/dry, mono/co-digestion	Biogas, digestate	192	<a href="#">Righi et al. (2013)</a> ; <a href="#">Nyitrai et al. (2023)</a>
Composting	Centralised or decentralised; windrow, in-vessel, static pile, etc.	Compost	176	<a href="#">De Boni et al. (2022)</a> ; <a href="#">Jalalipour et al. (2024)</a>
Integration of AD with composting	Composting of digestate	Energy, nutrient	39	<a href="#">Garkoti and Thengane (2025)</a> ; <a href="#">Mancini et al. (2019)</a>
Landfilling	Sanitary/unsanitary; with or without energy recovery	CH <sub>4</sub> , leachate	134	<a href="#">Liu et al. (2017)</a>
Incineration	With or without energy recovery (WtE)	Heat, electricity	125	<a href="#">Cheniti et al. (2024)</a>
Biorefinery-based production	Conversion of residues to materials/fuels	Feed, fertiliser, chemicals	24	<a href="#">Sarkar et al. (2023)</a> ; <a href="#">Siddiqui et al. (2021)</a> ; <a href="#">Zilia et al. (2023)</a>
Mechanical-biological treatment (MBT)	Pre-treatment for refuse-derived fuel (RDF) production	RDF	15	<a href="#">Boer et al. (2021)</a> ; <a href="#">Mayer et al. (2021)</a>
Hydrothermal carbonization (HTC)	Thermochemical conversion to hydrochar	Bio-solid fuel	4	<a href="#">Espinoza Pérez et al. (2022)</a>
Insect-based bioconversion	Black soldier fly larvae composting	Protein, feed, fertiliser	8	<a href="#">Salomone et al. (2017)</a> ; <a href="#">Ferronato et al. (2024)</a>
Open dumping	Uncontrolled disposal		11	<a href="#">Cheela et al. (2021)</a> ; <a href="#">Xiao et al. (2023)</a>



**Figure 3.** Categorisation of the current applied biowaste management methods

Source: Authors' own work

decentralised and community-scale service models offer lower transport impacts and foster local engagement (Righi *et al.*, 2013; De Boni *et al.*, 2022; Xiao *et al.*, 2023).

Typical AD configurations include wet or dry reactors and mono- or co-digestion with sewage sludge, producing biogas for energy (Goh *et al.*, 2025) and digestate as fertiliser (Nyitrai *et al.*, 2023). Composting is conducted through diverse technologies (windrow, aerated piles, in-vessel, tunnel, vermicomposting), yielding stabilised compost that is often used as a substitute for mineral fertiliser (Adhikari *et al.*, 2024; Guillaume *et al.*, 2023).

Although specific techniques vary, LCAs consistently indicate that both AD and composting achieve significantly lower environmental burdens than uncontrolled disposal or landfilling (e.g. Nyitrai *et al.*, 2023).

Integrating AD and composting is frequently reported as an effective combination of energy recovery and nutrient recycling (Garkoti and Thengane, 2025; Jalalipour *et al.*, 2024). However, system scale and feedstock availability are reported to influence outcomes. Centralised plants benefit from economies of scale, whereas decentralised systems can be preferable in contexts with limited logistics or dispersed waste sources (Tian *et al.*, 2021; Ni and Zhang, 2024).

**3.2.2 Other management approaches.** Incineration and landfilling are methods for the mixed treatment of biowaste with other fractions of MSW that can be applied under a waste-to-energy (WtE) umbrella (Wang *et al.*, 2023; Zhang *et al.*, 2025b). When energy recovery is efficient, incineration can offset fossil energy use and is reported to reduce climate impacts compared to landfilling, but it is generally reported to perform worse than AD or composting due to high upstream emissions (Bilgili *et al.*, 2022). On the other side, landfilling, both unsanitary and sanitary with energy recovery, is associated with high environmental impacts, mainly due to methane emissions (Cheela *et al.*, 2021; Xiao *et al.*, 2023).

Emerging technologies – biorefinery processes, MBT and HTC – represent a smaller share of the sample but show potential for future integration into circular bioeconomy models. More details on types of waste and outcome products from these technologies can be found in Supplementary Materials, Table S3 and S4, respectively.

Insect-based bioconversion is attracting attention as an alternative to conventional composting, producing high-value protein feed and organic fertiliser (Salomone *et al.*, 2017; Ferronato *et al.*, 2024).

Open dumping is mentioned in only six articles of the sample. Although it is widely reported as having high environmental impacts, it remains prevalent in developing countries, primarily driven by economic constraints (Cheela *et al.*, 2021).

3.2.3 *Types, composition and sources of waste.* The types of waste and their source are reported in Figure 4. The analysis revealed that the most frequently assessed type of waste is food waste (Figure 4.a) ( $n = 104$ ), followed by organic waste ( $n = 74$ ) and the organic fraction of MSW (OFMSW) ( $n = 49$ ). The results highlight that although a terminological variation emerges across the reviewed studies, many waste categories exhibit considerable compositional overlap (e.g. biowaste, organic waste, organic fraction). Consequently, differences in waste composition are reported to influence LCA results and may limit their comparability (Istrate *et al.*, 2023).

Regarding the source of waste, 53% of the waste studied in the collected sample is sourced from MSW, followed by households at 29%.

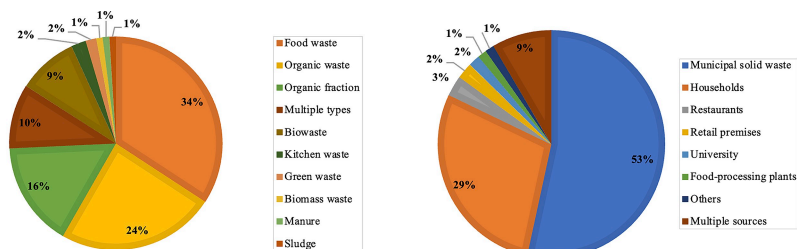
3.2.4 *Good environmental practices.* In this review, the term “good practices” refers to management options that are most frequently reported as environmentally favourable in the reviewed LCA studies. Although the methodological heterogeneity of LCA studies leads to obtaining results that may not be directly comparable (see also Section 3.3: Methodological Choices of LCAs for Biowaste Management), these practices were identified as recurring patterns in the literature.

Table 3 reports the identified hierarchy of good practices, which should be understood as an interpretative synthesis of recurring evidence in the reviewed literature, rather than an absolute ordering valid across all contexts. Overall, open dumping and unsanitary landfilling are the least sustainable options, while AD and composting consistently achieve lower life-cycle impacts. Hybrid configurations combining both are particularly recommended if allowed by local logistics and socio-economic conditions.

### 3.3 Methodological choices of life cycle assessments for biowaste management

The methodological review is structured according to the four LCA phases, in line with the approach described in Section 2. Materials and methods, and focuses on the key methodological elements identified for each phase (see Supplementary Materials, Table S5). The review highlights considerable heterogeneity in how LCAs are applied to biowaste management systems. Nevertheless, clear patterns emerge regarding each phase.

Table 4 summarises the main methodological features across the 308 reviewed studies.



(a) Terms used to refer to waste types.

(b) Source of waste.

**Figure 4.** Types and sources of waste (percentage allocation)

Source: Authors own work

**Table 3.** Relative environmental performance of biowaste management methods

Rank	Method/ configuration	Key advantage	Key drawbacks	References (examples)
1	Integrated AD + composting	Energy and nutrient recovery, low GHG emissions	Requires dual infrastructure	<a href="#">Le Pera et al. (2022)</a>
2	AD	Renewable energy, GHG mitigation	Digestate handling	<a href="#">Lévesque et al. (2023)</a> ; <a href="#">Nyitrai et al. (2023)</a>
3	Composting	Soil amendment, material recovery	Limited energy recovery	<a href="#">Lévesque et al. (2023)</a> ; <a href="#">Nyitrai et al. (2023)</a>
4	Incineration with energy recovery	Energy offset	Air emissions, residues	<a href="#">Liu et al. (2017)</a>
5	Sanitary landfilling (with energy recovery)	Energy recovery possible	High GHG and leachate impacts	<a href="#">Cheniti et al. (2024)</a>
6	Unsanitary landfilling / Open dumping		Severe local and global impacts	<a href="#">Cheela et al. (2021)</a> ; <a href="#">Xiao et al. (2023)</a>

3.3.1 *Goal and scope definition.* Most LCAs ( $n=269$ ) pursue comparative objectives, evaluating environmental trade-offs among biowaste treatment alternatives (e.g. [Aleisa and Alsaleh, 2024](#); [De Boni et al., 2022](#)), highlighting the focus on comparing alternative treatment practices to replace conventional ones while improving environmental sustainability.

The predominant FU is mass-related ( $n=258$ ), usually “1 tonne of waste”, providing straightforward comparability but overlooking potential benefits linked to energy or material recovery. However, output- or energy-based FUs are less frequently adopted, particularly in studies assessing valorisation processes (e.g. biochar or compost use).

SBs vary widely. Less than 20% of studies explicitly define SBs, suggesting limited methodological transparency. Although implicitly, around half of the reviewed articles adopt a waste-to-grave perspective, evaluating all the life cycle phases from waste collection to waste treatment and post-processing (production of products or disposal). The inclusion of post-processing and product use phases – for instance, compost application of biogas utilisation – allows for more comprehensive assessment ([Castellani et al., 2024](#)).

Indeed, because waste treatment generates multiple co-products (e.g. compost, biogas, digestate), system multi-functionality is a recurrent issue. Despite ISO’s recommended hierarchy ([ISO, 2020](#)), practitioners often rely on the substitution or avoided-burden method, adopted in two-thirds of the studies, as it allows crediting avoided conventional products such as synthetic fertilisers or grid electricity. Allocation methods – mainly mass, energy or economic-based – are used in about 10% of studies, while full system expansion remains rare due to data and modelling complexity. Only a minority of papers perform sensitivity tests on allocation choices, even though these can strongly affect results.

3.3.2 *Inventory analysis.* Regarding the life cycle inventory (LCI) analysis, data sources are predominantly secondary, mostly drawn from the ecoinvent database ( $n=143$ ) and complemented by literature data. Primary data are poorly available and generally limited to waste composition, transport distances or facility-specific inputs. Therefore, the reliance on secondary data underscores the need for sensitivity or uncertainty analyses to assess data quality and variability.

In addition, some articles perform a comparative analysis based on secondary data from multiple literature sources (e.g. [De Boni et al., 2022](#)). For example, [De Boni et al. \(2022\)](#) adopt the results from [Cherubini et al. \(2009\)](#) and [Mondello et al. \(2017\)](#) to compare the global warming potential associated with the landfilling and incineration of 1 tonne of waste,

**Table 4.** Main methodological characteristics in the reviewed sample

Aspect	Main options/ shares	Notes	References (examples)
Goal of the study	Comparative analysis (87%), hotspot analysis (11%), other (2%)	LCAAs mainly compare alternative treatment options	Aleisa and Alsaleh (2024); Nhubu <i>et al.</i> (2020)
Functional unit (FU)	Mass-based (84%, mostly 1 tonne of waste), energy-based (5%), output based (e.g. compost, biochar) (11%)	Mass-based FUs dominate (predominantly input-based)	Adhikari <i>et al.</i> (2024); Castellani <i>et al.</i> (2024)
System boundaries (SBs)	Not explicitly defined (83%), cradle-to-grave (5%), cradle-to-gate (5%), others (7%)	Although implicitly, waste-to-grave SBs are mainly adopted	Castellani <i>et al.</i> (2024); Liu <i>et al.</i> (2017)
Multi-functionality approach	Substitution/ avoided burden (66%), allocation (10%), system expansion (3%), not specified (21%)	Substitution preferred despite ISO's hierarchy	Aleisa and Alsaleh (2024)
Inventory data	Secondary data only (48%), mixed (45%), primary only (3%)	Ecoinvent most used database; limited use of primary data	Nyitrai <i>et al.</i> (2023)
LCA software	SimaPro (31%), EASETECH (13%), LCA for Experts (11%), OpenLCA (2%), unspecified (43%)	Reflects database accessibility and regional preferences	Arfelli <i>et al.</i> (2023)
Impact assessment methods	ReCiPe (25%), CML (21%), IPCC (17%), other (37%)	ReCiPe and CML dominate for comprehensive midpoint coverage; IPCC is preferred for climate change analyses	
Impact categories	Climate change (96%), acidification (47%), eutrophication (42%), human toxicity (43%), photochemical ozone (41%), energy demand (17%)	GHG emissions dominate assessment focus	Alsaleh and Aleisa (2023); Ni and Zhang (2024)
Sensitivity analysis	Performed in 51% of studies	Mainly on energy and transport parameters	Ni and Zhang (2024)
Uncertainty analysis	Performed in 17% of studies	Monte Carlo simulation most common	Lewerenz <i>et al.</i> (2023)

respectively. However, the use of multiple data sources may reduce comparability due to different methodological and modelling choices.

It is worth mentioning that the LCI can be constructed using either an attributional approach ( $n = 40$ ) or a consequential approach ( $n = 41$ ). Some articles indicate that they have utilised both approaches ( $n = 2$ ) (Bernstad Saraiva *et al.*, 2017; Lilonfe *et al.*, 2024), whereas the majority of the sample ( $n = 226$ ) do not specify which approach was used.

Regarding the software, SimaPro ( $n = 97$ ) (PRé Sustainability, 2025) is the most widely used, probably due to its integration with ecoinvent database and user familiarity. Other tools (e.g. EASETECH ( $n = 39$ ) (Clavreul *et al.*, 2014), LCA for Experts ( $n = 35$ ) (Sphera, 2025), OpenLCA ( $n = 5$ ) (OpenLCA, 2024)) are also employed. However, no single tool outperforms others universally; thus, the choice should depend on database compatibility and practitioner expertise.

**3.3.3 Impact assessment.** Regarding the life cycle impact assessment (LCIA), ReCiPe (RIVM, 2024) ( $n = 78$ ) and CML (CML-IE, 2016) ( $n = 63$ ) are the most commonly employed impact assessment methods, followed by the IPCC (IPCC, 2019) ( $n = 51$ ). Among the many impact categories investigated, climate change or global warming is the most frequently considered ( $n = 295$ ). Indeed, some studies focus on this impact category due to the reported concerns about GHG emissions resulting from biowaste management methods (e.g. Bian *et al.*, 2022; Ni and Zhang, 2024).

Other frequently assessed impact categories include acidification potential ( $n = 146$ ), human toxicity ( $n = 132$ ), eutrophication ( $n = 128$ ) and photochemical ozone formation ( $n = 125$ ). It is also noteworthy that energy-related impact categories, such as cumulative energy demand (e.g. Alsaleh and Aleisa, 2023), are examined in numerous studies ( $n = 53$ ).

**3.3.4 Interpretation.** Slightly more than half of the sample ( $n = 156$ ) includes a sensitivity analysis, usually investigating energy-related parameters ( $n = 79$ ), such as electricity mix, recovery efficiency and consumption. Transport also receives attention in many articles ( $n = 36$ ), examining how different transport distances or fuel substitution affect results, while only about 7% of the sample ( $n = 23$ ) considers waste composition or separation rate.

In contrast, only 17% of the sample ( $n = 51$ ) conduct a quantitative uncertainty analysis, most commonly via Monte Carlo simulation ( $n = 35$ ).

On one hand, the limited focus on waste collection and separation as important factors may stem from the higher accessibility of relevant primary data. On the other hand, several assumptions concerning energy consumption, recovery efficiency, transportation distances and fuel types make these factors significant. Moreover, these parameters deserve closer examination when evaluating different scales of treatment plants (e.g. Ni and Zhang, 2024).

## 4. Discussion

The discussion section is structured around the main conceptual findings emerging from the study, encompassing:

- synthesis of the key findings;
- methodological implications;
- managerial implications; and
- future research agenda.

### 4.1 Synthesis of key findings

This review provides an integrated understanding of the current application of LCA to municipal biowaste management systems, combining bibliometric, technical and methodological perspectives.

The bibliometric analysis highlights a consolidation of the literature around AD and composting, with comparatively limited attention to alternative service configurations. This concentration suggests a potential gap in the exploration of diverse organisational models and may limit the transferability of LCA findings across different practical contexts.

From a technical perspective, the results confirm that waste composition plays a key role in influencing environmental outcomes, as variations in feedstock characteristics can lead to differences in process performance and affect the consistency of results across studies.

In addition, the analysis shows that the environmental performance of biowaste management systems is strongly influenced by service-related aspects, particularly system scale and organisational configuration. The comparison between centralised and decentralised systems highlights that their relative performance depends on contextual factors. Centralised systems tend to be more efficient where large and homogeneous waste streams justify economies of scale and transport impacts remain limited. Conversely, decentralised systems may achieve better environmental outcomes in contexts characterised by dispersed feedstock, limited infrastructure, shorter transport distances and stronger local stakeholder involvement.

These findings emphasise that biowaste management cannot be evaluated solely based on technological performance, but must be understood as a service system in which logistical, organisational and social dimensions play a critical role.

#### *4.2 Methodological implications*

The review highlights several methodological implications for the application of LCA to biowaste management systems, which directly affect the comparability of results, their interpretation, and their use in supporting decision-making.

Overall, the reviewed studies highlight a set of recurring methodological patterns, including:

- a persistent reliance on mass-based FUs and predominance of waste-to-grave SBs;
- a preference for substitution approaches to address multi-functionality, often without explicit sensitivity testing;
- a limited use of primary data and uncertainty assessment; and
- a predominant focus on climate change as the main assessed impact category.

These patterns highlight the strong influence of modelling choices on LCA outcomes. For instance, the widespread use of mass-based FUs, while facilitating comparability, may overlook the benefits associated with energy and material recovery in valorisation processes. Similarly, the reliance on secondary data can introduce inconsistencies, particularly when different assumptions are not harmonised. In addition, the selection of impact categories plays a crucial role in shaping the interpretation of results. While climate change is consistently assessed, other relevant indicators are not always systematically included, despite their importance in evaluating WtE systems and circular bioeconomy strategies. Finally, the interpretation phase remains one of the weakest aspects of current LCA practice in this field. The limited use of uncertainty analysis and scenario testing reduces the robustness of conclusions, particularly in studies relying heavily on assumptions and secondary data. Strengthening this phase through more systematic uncertainty and sensitivity analyses would significantly enhance the reliability and decision-support value of LCA results. In particular, these aspects are critical when evaluating trade-offs between system scale, transport requirements and energy recovery options across different management configurations.

#### 4.3 *Managerial implications*

The findings of this review also provide relevant insights for practitioners and decision-makers involved in the design and management of biowaste systems.

Firstly, the results highlight that the environmental performance of biowaste management options cannot be generalised across contexts. Therefore, decision-makers should carefully consider local conditions and contextual factors when selecting and implementing management strategies.

Secondly, the analysis underscores the importance of adopting a service-oriented perspective, in which technological choices are evaluated together with organisational and logistical aspects. In this regard, integrated and locally adapted solutions, such as hybrid configurations or decentralised systems, may offer advantages under specific conditions.

Finally, the results point to the need for more robust and transparent LCA applications to support decision-making. Improving data quality, clearly defining system boundaries and assumptions, and incorporating uncertainty analysis can enhance the reliability and usefulness of LCA as a decision-support tool in the context of municipal biowaste management.

#### 4.4 *Future research agenda*

This review also identifies several open questions and directions for future research.

Firstly, further studies are needed to improve the comparability of LCA results by developing more consistent approaches to key methodological aspects, such as FUs, SBs and multi-functionality management. In particular, the integration of output- or function-based indicators alongside mass-based FUs could provide a more comprehensive representation of valorisation processes.

Secondly, additional empirical research is required to better understand the context-dependent performance of different biowaste management configurations, particularly with respect to centralised and decentralised systems under varying geographical, infrastructural and socio-economic conditions.

Thirdly, future work should strengthen the use of primary data and uncertainty analysis to enhance the robustness of LCA results, especially in studies relying on secondary data and assumptions.

Finally, further research should expand the scope of assessment beyond climate change by systematically including additional impact categories and by integrating service-related and organisational dimensions into LCA modelling. This would improve the relevance of LCA as a decision-support tool for the design of sustainable biowaste management services.

### 5. **Conclusions**

This study provided a comprehensive overview of the state of the art in LCA for municipal biowaste management services and systems, analysing 308 peer-reviewed articles through bibliometric, systematic and content analysis methods.

The results confirm the growing attention to this topic, particularly in China and other developed countries. The *Journal of Cleaner Production and Waste Management* were identified as the most productive journal sources, while authors' keywords revealed a dominant focus on food waste and AD.

Among the treatment methods, AD and composting are the most commonly assessed technologies due to their environmental advantages. Centralised configurations prevail over decentralised ones, although integrated approaches combining AD followed by composting of the digestate often show favourable environmental outcomes. Such integration can reduce energy consumption through biogas recovery and improve nutrient retention, but its

applicability depends on local service organisation, socio-economic and infrastructural conditions.

Regarding the methodological aspects of LCAs for biowaste management, the results highlight a persistent reliance on mass-based FUs and a limited use of sensitivity and uncertainty analyses, despite the high reliance on secondary data. Future research should explore the use of output-based FUs and systematically assess uncertainty to strengthen the robustness of results.

In summary, the bibliometric patterns, the analysis of management practices, and the identified methodological implications highlight that improving transparency, increasing consistency in methodological choices, and strengthening uncertainty analysis are crucial to enhance the comparability and reliability of LCAs of biowaste management services and systems.

This review contributes to advancing knowledge on biowaste management services by identifying common methodological practices and highlighting context-dependent good practices for different treatment options. By adopting a service- and system-oriented perspective, the study provides a basis for future research aimed at improving methodological consistency and the decision-support relevance of LCAs for municipal biowaste management. In this context, the findings are primarily relevant for local authorities, waste management service operators and LCA practitioners. Specifically, more consistent and comparable LCAs can support public decision-making, procurement processes, and the evaluation of alternative management service configurations within decarbonisation and circular economy strategies. In addition, it should be pointed out that social aspects, such as acceptability and local participation, are also recognised as relevant for biowaste management practices implementation, although they are beyond the scope of the present review.

However, this study also has some limitations, mainly related to the restriction to English peer-reviewed journal articles from Scopus (SP) and Web of Science (WoS), which may have excluded relevant grey literature and regional case studies. In addition, while the FLAVIA-LCT framework proved effective for structuring a large and heterogeneous sample of literature, its application to municipal biowaste management services required careful interpretation to adequately capture operational and service-related dimensions that are not always central in traditional LCA-oriented reviews. Moreover, the reviewed LCAs adopted heterogeneous modelling choices that can lead to variations in impact results, limiting cross-study comparability. These aspects should be addressed in future research to strengthen the robustness and representativeness of findings.

Overall, this review provides a solid basis for designing more consistent, comparable and service-oriented LCAs of municipal biowaste management systems, thereby supporting local decision-making and the implementation of sustainable circular economy strategies.

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### Supplementary material

The supplementary material for this article can be found online.

### Corresponding author

Alice Mondello can be contacted at: [alice.mondello@unime.it](mailto:alice.mondello@unime.it)