Review

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Challenges and Issues of Life Cycle Assessment of Anaerobic Digestion of Organic Waste

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Article

Challenges and Issues of Life Cycle Assessment of Anaerobic Digestion of Organic Waste

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Abstract: Life Cycle Assessment (LCA) is a widely used tool to measure the environmental sustainability of products or processes. Integrating LCA into the assessment of waste diversion strategies recognizes current waste diversion strategies are insufficient to effectively stem the global impacts of waste particularly with increased pressure to recover organic and inorganic materials to reduce landfill impacts and promote the circular economy. Historically, waste diversion efforts in municipalities and industries focused on higher-profile inorganic wastes, such as plastics and other recyclables. However, organic waste is increasingly identified as a key waste fraction that must be effectively managed and regulated. This research surveys published LCA studies from 2019 to 2023 focusing on the anaerobic digestion (AD) of organic waste. Notable conclusions include the lack of studies comparing AD with the latest treatment options such as co-gasification; the insufficient attention to the LCAs on biogas upgrading methods; and the monetization of LCA results using carbon credits. In addition, more than 50% of reviewed LCA studies concluded the results with a sensitivity analysis which was not a common practice before 2019 in LCA studies in anaerobic digestion. This signifies the increasing need to understand uncertainty in the circumstances governing applying AD to wastes. Finally, neglecting the combined effect of several parameters in sensitivity analysis might have reduced the accuracy of the sensitivity analyses in the reviewed LCAs. Overall, LCAs conducted on AD-related applications vary widely in terms of scope and consistency, implying that the outcomes may not be as applicable as intended. The identified challenges, issues, and other findings related to this research are expected to help standardize LCA procedures as applied to AD to promote greater comparability.

Keywords: life cycle assessment; anaerobic digestion; organic waste; review

1. Introduction

Population growth, urbanization, upgrades in consumer patterns, and modern lifestyles of the global population have increased global waste. Waste generation in high-income countries accounts for 34% of the total global waste generation while low-income countries account for only 5% (Kaza et al., 2018). Different factors contribute to this global solid waste problem on different scales. Kaza et al., (2018) concluded that East Asia and the Pacific region were the largest contributors to global solid waste generation (responsible for 23%), and the Middle East and North Africa (responsible for 6%) were the smallest contributors in 2016 (Kaza et al., 2018). Waste from human consumer patterns threatens the environment and human health directly and indirectly. Unmanaged or poorly managed solid waste pollutes the oceans, blocks sewers, transmits diseases, increases respiratory problems, and harms animals too (Sharma & Jain, 2020). Also, unmanaged solid waste from dumps or poorly designed/maintained landfills results in leachate problems. These can contaminate surface water and groundwater, impacting both potable water for human use and the broader ecosystems (Sharma & Jain, 2020). It is necessary to develop improved design, management, and treatment alternatives for this global solid waste problem while trying to reduce waste generation. LCA is one effective tool for assessing if such efforts are effective.

Despite a substantial increase in waste generation in recent years, waste management strategies have improved slowly and not necessarily uniformly. Globally, the major solid waste disposal method remains as open dumping and landfilling for approximately 70% of the total global solid waste (Kaza et al., 2018) because of the low investment and technology needed for landfills compared to more advanced methods of solid waste management (Dastjerdi et al., 2021a). Uncontrolled landfilling – essentially "dumping" - accounts for a significant portion of the Landfill Gas (LFG) emissions consisting of methane (CH_4) and carbon dioxide (CO_2) which are major contributors to global GHG emissions. In the US, landfills accounted for approximately 16.9% of the total CH_4 emissions in the year 2021 (Epa, 2021). In addition, uncontrolled landfilling also creates problems such as toxic and hazardous leachate, such as arsenic and cadmium contamination, which could contaminate the groundwater and soil, rendering them unusable for humans and biota for an extended period (Mavakala et al., 2016).

While the world is committed to addressing the climate change issue by agreeing to the Paris Agreement in 2015 to reduce the global average temperature increase to 1.5^{0}C by the end of this century, these emissions from landfills and open dumping are major obstacles. LFG mainly consists of CH_4 (50-55%) and the rest is CO_2 (Dastjerdi et al., 2021a). The global warming potential value of CH_4 is 28 times higher than CO_2 (Adghim et al., 2020). To stop the contribution of this CH_4 in LFG to the global warming increase, more diversion from landfilling is critical.

In Canada, 40% of the residential waste and 20% of the ICI (Industrial, Commercial, and Institutional) waste are organic waste (OW) (Staley & Boxman, 2021). Canada has introduced OW diversion targets for each province. Ontario has targeted to divert 50-70% of its organic waste from landfills by 2025(Staley & Boxman, 2021). British Columbia has targeted to divert 95% of the OW from agriculture, industrial, and municipal waste (Staley & Boxman, 2021). Previous studies have compiled the amount of organic waste diverted from landfills in different provinces of Canada, with Ontario being the largest OW contributor, and out of that, approximately 31% has been diverted from landfills (Environment and Climate Change Canada., 2020). Because of these ambitious diversion targets – and the significant contribution of organic waste to overall waste – it is critical to target the degradable organic fraction.

Several solutions are being used to divert this solid waste from landfills. Composting, incineration (I), hydrothermal carbonization (HTC), pyrolysis (Py), and anaerobic digestion (AD) are the main methods of diverting solid waste from landfilling in the world. Among these methods, AD is one of the widely adopted systems in most countries. In Canada, the most common methods to manage organic solid waste are AD and composting (Staley & Boxman, 2021). According to this report, there were 59 AD facilities established by 2019 which they use to process the organic waste within Canada. The USA also has increased its AD facilities from 12 to 68 from 2005 to 2021 (EPA, 2021). Because AD is being increasingly adopted, it is important to understand and review the use of AD in organic waste digestion to determine how effective it is in truly addressing waste management needs, and to discover ways to improve this process further.

Any waste disposal method should be environmentally sustainable to achieve the global targets to avoid climate change and other environmental impacts. LCA can assess the potential environmental benefits and impacts of a product during its whole life cycle (International Organization for Standardization, 2006). Previous researchers have conducted such studies to investigate the environmental effects of AD. Some studies have compared AD with other solid waste treatment methods using LCA (Lee et al., 2020; Mayer et al., 2021). Several other LCA studies have focused on the environmental impacts of changing the parameters involved with AD such as inoculum type, incubation time, and the substrate: inoculum ratio (S: I) (Demichelis et al., 2022). Also, there are several review studies done related to the AD of organic waste considering different aspects. Liu et al. (2023) reviewed past studies about anaerobic co-digestion with food waste and summarized the challenges, improvement strategies, and influencing factors of different biomass wastes (Liu et al., 2023). Yaser et al. (2022) reviewed the existing AD and composting processes on campus premises, the adoption of these campus facilities, and their future direction considering the global context (Yaser et al., 2022).

Despite the above references, there are relatively few review studies about LCAs conducted on AD, and not many comprehensively account for factors considered to be currently critical. Nhubu et al. (2021) conducted a review study on the LCA studies on the AD of degradable fractions of municipal solid waste. Still, that study did not consider other industrial OW types such as animal manure, slaughterhouse waste, and agricultural waste (Nhubu et al., 2021). Mulya et al. have systematically reviewed the LCA studies on solid waste management techniques in common but not specifically AD (Mulya et al., 2022).

When it comes to OW, several literature reviews have focused on the LCA aspects of the treatment options available. Sridhar et al. (2021) reviewed the previous LCAs undertaken on the conversion of food waste to energy (Sridhar et al., 2021). In this paper, LCA studies of treatment methods such as incineration, landfill, composting, pyrolysis, AD, and biochemical methods were reviewed. Esteves et al. (2019) published a review paper from their literature findings focused on the LCA studies on treatment methods for animal manure to extract energy and biofertilizers (Esteves et al., 2019). They considered the AD process mainly in their review paper, but the considered substrate is only animal manure. Dastjerdi et al. (2021) and Mayer et al. (2019) conducted systematic reviews of the LCAs done on different waste-to-energy valorization technologies in general and they comprehensively analyzed the LCA aspects, and its compliance levels and compared the results of those studies (Dastjerdi et al., 2021b; Mayer et al., 2019). However, Mayer et al. (2019) published their review paper in February 2019 where no LCA studies done in 2019 were included (Mayer et al., 2019). Even though the other review study done by Dastjerdi et al. (2021), was published in December 2020, only one LCA study done in 2020 was considered in that review paper (Dastjerdi et al., 2021).

The latest trends of organic, waste-diverting policies globally, including developed countries in North America and Europe, have increased the importance of AD as a waste diversion alternative. Also, recently researchers have started investigating the connection between AD and the United Nations Sustainable Development Goals (UNSDGs) under environmental, economic, and social dimensions (Piadeh et al., 2024). With these new macro-level developments, it is crucial to investigate and review the LCA studies on AD that have not been conducted for the published research between 2019 to 2023. There appears to be a clear gap in literature review studies focusing on the LCA studies on AD of OW from 2019 to 2023. The latest trend of organic, waste-diverting policies globally, including developed countries in North America and Europe, has increased the importance of AD as a waste diversion alternative. Also, recently researchers identified the connection between AD and the United Nations Sustainable Development Goals (UNSDGs) under environmental, economic, and social dimensions (Piadeh et al., 2024). Because of these macro-level developments, it is crucial to compare the latest contributions to this research area.

This research paper focuses on addressing the above-identified research gap by reviewing the latest LCA studies conducted specifically on the AD of OW. With that aim, this paper will elaborate on and compare LCA methods, study results, drawbacks, and how results have been presented to emphasize the challenges and issues with conducting LCAs on the AD of OW. This study's findings will help ensure the consistency of future LCA studies conducted on AD.

2. Review Methodology

There are different types of review studies, including scoping review, literature review, systematic review, meta-analysis, and critical review. This paper adopts a *systematic review approach* which identifies the most significant items in the field, summarizing and compiling them (Grant & Booth, 2009).

The first phase of the review was to filter and separate the most relevant research papers for investigating the life cycle assessments performed on the anaerobic digestion of organic waste. For that purpose, the Engineering Village research database was used, and the initial keyword search was conducted using the keyword combination, “life cycle assessment” AND “anaerobic digestion” AND “organic waste”.

Figure 1 shows the filtering phase of the review methodology. This keyword combination resulted in 243 research papers. After that, it was reduced to 109 by limiting the results only to journal papers and limiting the time frame from 2019 to 2023. Next, literature review papers were identified by reading the topic of every resulting research paper. There were 20 literature review papers that were later rejected. Then, by reading the abstracts of the remaining papers, 43 papers were identified as irrelevant to this study because they were not focused on the life cycle assessment of the anaerobic digestion of organic waste. Some of those studies had considered different approaches such as machine learning-based approaches to evaluate the environmental and economic impacts of the solid waste management strategies but did not use the LCA tool. Some papers discussed the LCA studies conducted on organic waste management using other technologies such as hydrothermal carbonization and incineration but not AD. In the end, 46 journal papers were selected for this review study.

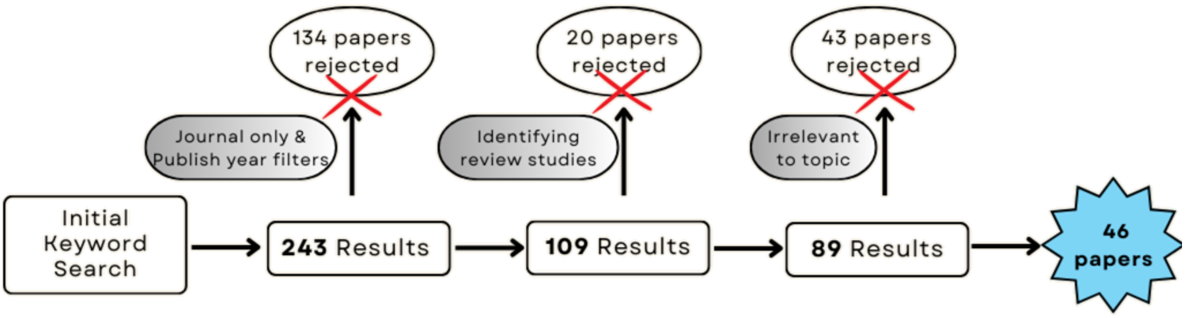

Figure 1. Papers Filtering Phase.

The published literature reveals that most of the previous research efforts (67%) focused on the environmental performance of AD while the remainder (33%) considered both life cycle, environmental, and economic performance. Tominac et al. (2021) identified a similar pattern highlighting the lack of comprehensive studies that focused on the triple bottom line of sustainability (Tominac et al., 2021). Furthermore, it is important to examine the geographic distribution of the research contributions to this research area. Figure 2 illustrates how the reviewed studies are distributed by geographic region. The origin of the research study was decided either by examining the considered case study or the referred country-specific data sources.

Most of the studies reviewed (45%) are from the European region. The European Union (EU) has taken steps to regulate the EU countries to limit the landfilling of OW for a significant period (Francini et al., 2019). In the European Waste Framework Directive, landfilling has been defined as the least favorable option in the waste hierarchy (Mayer et al., 2020). Because of these guidelines and regulations, EU countries have been conducting research in this area for a long time.

Because the types of organic waste and their characteristics affect AD and its output, so too do the LCA results vary. At the same time, climate conditions such as temperature, precipitation, and humidity affect the organics intended for anaerobic digestion. These weather-related conditions vary widely according to the geographic location (Balcioglu et al., 2022; Sahoo & Mani, 2019). In addition, LCA results depend on the regional electricity grid mix and the availability of feedstock around the study location (Y. Wang et al., 2023)

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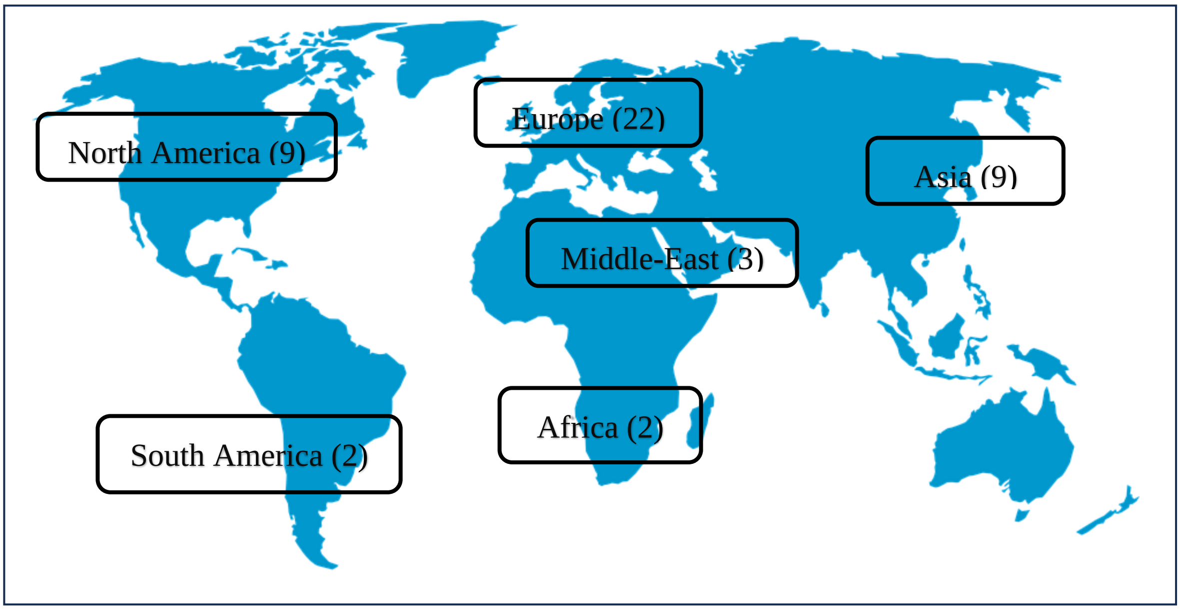

Figure 2. Geographical distribution of the reviewed LCA studies.

2.1. Bibliometric Analysis of Previous Studies

The keywords in the title and the abstract of the reviewed 46 research papers from the Engineering Village database were evaluated using the VOS viewer software. The software identified 27 keywords in the title and abstract of the 46 research papers. The connection lines are drawn considering the co-occurrence of those keywords as shown in the network visualization map in Figure 3. The concept of co-occurrence is the appearance of two terms in one paper together. The keywords identified by the software as the highest occurrence were life cycle (48), anaerobic digestion (47), global warming (20), eutrophication (17), and municipal solid waste (19). The size of the circles and the labels in that map reflect the frequency of appearance of that keyword in the research papers. The distance between the keywords reflects the appearance of those words together in the reviewed papers. According to Figure 3 "anaerobic digestion", "life cycle", and "global warming" can be verified as the highest co-occurring keywords because of their large circles and location close to each other.

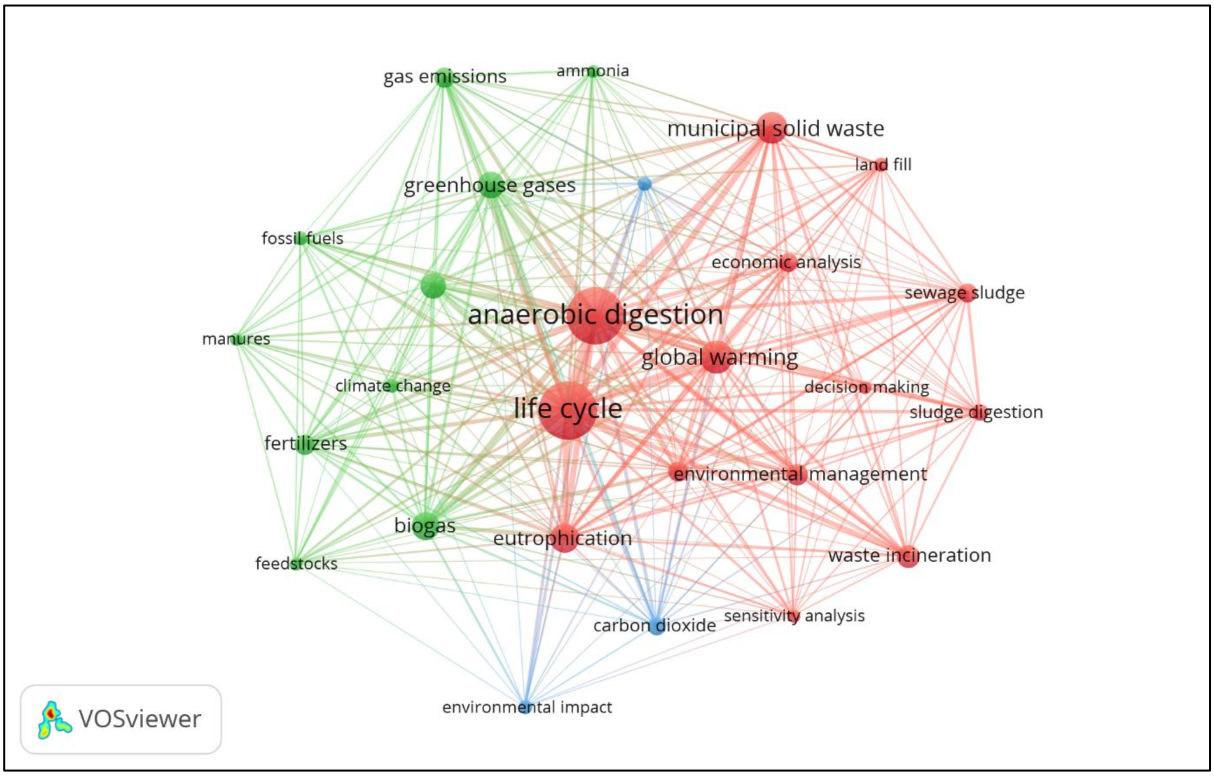

Figure 3. Network Visualization Map for the scientific landscape of the papers in LCA on AD of OW.

3. Results

The main four steps of the standard LCA as mentioned by ISO 14044 are goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and life cycle results interpretation (International Organization for Standardization, 2006). The extracted data from the literature survey were reviewed under these four topics to identify research patterns, challenges, and issues associated with each step of conducting LCAs.

3.1. Goal and Scope Definition

This is the first step that lays the foundation of the LCA. The LCA's scope and goal should be defined. Another major aspect under the goal and scope definition stage is the functional unit and the system boundary. The functional unit must be selected in such a way that it aligns with the goal and scope of the LCA (International Organization for Standardization, 2006).

3.1.1. Functional Unit

In 98% of the LCAs reviewed (45 papers), the goal was to compare the environmental impacts of different scenarios defined at the beginning of the study. Only one LCA case study had been conducted for an existing facility without considering alternative scenarios (Weligama Thuppahige & Babel, 2022).

One significant component under the goal and scope definition stage is the functional unit (FU) of the LCA. Out of 46 reviewed articles, 37 used a FU by considering the input feedstock for the AD process while 8 used a FU focusing on the main output of the AD process. Only one study did not define a FU. Among the 37 studies, 25 used a unitary functional unit such as “1 t of OFMSW”, “1t of food waste in bins”, and “1t of wet manure”, while some used a fixed amount of feedstock though it is not necessarily one. Rather than using unitary feedstock amount, by using a fixed amount of waste, those LCA studies could provide recommendations for the existing plants or farms according to the sizes (Jiang et al., 2021). Another reason for using a fixed amount of feedstock without using a unitary

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amount is that during inventory creation the quantities will be very small if the FU selects a unitary amount (R. Chen et al., 2022). Five LCA studies used the FU as the feedstock amount as a function of time such as "the annual amount of treated waste", and "End of life management of FW & SS generated by a municipality of 50,000 people in the US for 20 years" (Pasciucco et al., 2023; Nyitrai et al., 2023). Another 8 LCAs used the unit amount of energy (heat, electricity) or unit amount of natural gas produced as their FU. Van den Oever et al. (2021) used "1 MJ equivalent amount of CBG delivered to the vehicle tank" and Sahoo & Mani (2019) used "one gallon of gasoline-equivalent of BioCNG produced and consumed as a transportation fuel" as the FU in their LCAs (Sahoo & Mani, 2019; van den Oever et al., 2021).

One major reason for this variation in selecting the FU in the LCAs is the unavailability of specific Product Category Rules (PCRs) for LCA studies on AD. Because of that, researchers have defined the FUs according to the goal of their LCA. PCRs are defined in the ISO standard as the set of specific rules for, requirements, and guidelines for developing Type III environmental declarations for one or more product categories (International Organization for Standardization, 2006). The purposes of PCRs are to accurately quantify environmental attributes, transparently communicate the results, and for comparison among the products in the same category (Ingwersen & Stevenson, 2012). PCRs are developed for several categories such as dairy, horticulture, wood-plastic boards, and laundry detergents focusing on different parts of the world (Subramanian et al., 2012). In these PCRs, functional units, scope and boundaries, calculation rules, allocation methods, and impact categories to be considered are defined (Subramanian et al., 2012).

Also, this functional unit may vary according to the stakeholder preferences in a project. As an example, government agencies are interested in managing OW and they may prefer to conduct the LCA using a FU of feedstock. Some other stakeholders such as the AD plant might have more interest in the main product of the AD process, which is biogas. AD plant will prefer to investigate the environmental impacts from an energy generation point of view. Table 1 presents an overview of the different FUs used in the reviewed articles.

Table 1. Use of different Functional Units in the reviewed LCAs.

No	Study	Context of AD	Type of Functional Unit (FU)					
			Feedstock – fixed amount	Feedstock - Unitary	Feedstock – As a function of time	Energy – Unit Amount	Fuel – Unit Amount	FU – Not Defined
1	(S. Wang et al., 2021)	Slaughterhouse waste	✓					
2	(Mancini et al., 2019)	OFMSW	✓					
3	(R. Chen et al., 2022)	Sewer sludge	✓					
4	(Behrooznia et al., 2020)	OFMSW	✓					
5	(González et al., 2020)	OW (4th range vegetable & fruits)	✓					
6	(Vinitskaia et al., 2021)	MSW	✓					
7	(Li et al., 2021)	Diary manure and cucumber waste	✓					
8	(Demichelis et al., 2022)	OFMSW		✓				

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9	(Lee et al., 2020)	FW, YW & Biosolids	✓
10	(J. Wang et al., 2021)	OFMSW	✓
11	(Adghim et al., 2020)	OFMSW	✓
12	(Zhen et al., 2023)	Cow Manure	✓
13	(Gupta et al., 2022)	FW	✓
14	(X. Zhou et al., 2022)	FW and Cow Slurry	✓
15	(Lin et al., 2021)	Sewer Sludge	✓
16	(Gálvez-Martos et al., 2021)	Cassava Starch Agro-Industrial	✓
17	(Weligama Thuppahige & Babel, 2022)	OFMSW	✓
18	(Mendieta et al., 2021)	Sugar Cane	✓
19	(Mancini et al., 2019)	OFMSW and Graden Waste	✓
20	(D. Wang et al., 2020)	MSW	✓
21	(Somorin et al., 2023)	Agri-Food waste	✓
22	(H. Zhou et al., 2022)	Sewage Sludge	✓
23	(Sardarmehni & Levis, 2021)	MSW	✓
24	(Panigrahi et al., 2022)	Yard Waste	✓
25	(Valenti et al., 2020)	Cattle & Poultry Manure, Whey & Silage, Olive Pomace	✓
26	(Nordahl et al., 2020)	OFMSW	✓
27	(Shih et al., 2023)	Swine Manure	✓
28	(S. Chen et al., 2023)	MSW	✓
29	(Gadaleta et al., 2023)	MSW	✓

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30	(Arfelli et al., 2023)	Fish Leftovers	✓				
31	(Guillaume et al., 2023)	OFMSW	✓				
32	(Pasciucco et al., 2023)	OFMSW & Sewer Sludge		✓			
33	(Nyitrai et al., 2023)	FW & Sewer Sludge		✓			
34	(Francini et al., 2019)	OFMSW & Sewer Sludge		✓			
35	(Jiang et al., 2021)	Pig Manure & FW		✓			
36	(Castellani et al., 2023)	OFMSW		✓			
37	(Orner et al., 2022)	Sewage Sludge HSOW		✓			
38	(Mayer et al., 2021)	OFMSW, FW & Wood Waste			✓		
39	(Shinde et al., 2021)	SSOW, Grease trap sludge, Ley Crops			✓		
40	(Mayer et al., 2020)	OFMSW			✓		
41	(Balcioglu et al., 2022)	Cattle Manure, Chicken Manure, Slaughterhouse Waste, Cattle Slurry			✓		
42	(Bacenetti et al., 2019)	Animal Slurry, Cereal Silage			✓		
43	(van den Oever et al., 2021)	Animal Manure & OFMSW				✓	
44	(Sahoo & Mani, 2019)	Diary Manure & FW				✓	
45	(Y. Wang et al., 2023)	FW & Animal Manure				✓	
46	(Tominac et al., 2021)	OFMSW					✓

3.1.2. System Boundary

Defining the system boundaries is also a crucial aspect of an LCA. According to the goal of the study and the availability of data, researchers tend to have different system boundaries in their studies. Among the reviewed articles, cradle-to-gate, cradle-to-grave, cradle-to-cradle, gate-to-gate, and gate-to-grave are the five main boundary conditions identified. Even though the first three system boundaries were frequently used, the gate-to-gate system boundary was used only in 3 studies (Castellani et al., 2023; Panigrahi et al., 2022; Shih et al., 2023). Gate-to-grave system boundary was found in 2 studies (Gadaleta et al., 2023; Nyitrai et al., 2023). Those studies have not considered waste transportation impacts. Panigrahi et al. (2022) did not incorporate waste collection, transportation to the AD plant, and application of the produced energy (Panigrahi et al., 2022). Castellani et al. (2023) also did not include the curbside municipal waste collection and transport

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phases in their study because that phase had the same impacts on the LCA results for both the compared scenarios in that study (Castellani et al., 2023).

Most of the reviewed LCA studies have used either cradle-to-grave or cradle-to-gate system boundaries. These studies have considered waste collection from the point of generation, transportation to the AD plant, sorting, and pretreatment where applicable, AD process, export of biomethane for use in vehicles after purification or electricity and heat generation using in-house CHP plant, and land application of digestate after further treatment as the main sub-processes. Three of the reviewed LCA studies considered the mixing of energy crops such as Ley crops, Miscanthus, and Cereal with OW as the substrate for their AD process (Bacenetti et al., 2019; Sahoo & Mani, 2019; Shinde et al., 2021). Crop cultivation, harvesting, sorting, and transportation of the harvested crops were also included in these studies which deviated from the usual boundaries in the other LCA studies.

Another highlighted aspect was the construction phase of the AD plant. Out of 46 reviewed articles, only 6 articles considered the construction phase of the AD plant (Bacenetti et al., 2019; Balcioglu et al., 2022; Castellani et al., 2023; R. Chen et al., 2022; Li et al., 2021; Mendieta et al., 2021). All the others excluded the construction phase. Jiang et al. (2021) excluded the construction and decommissioning phases of treatment infrastructure in their LCA since they occur once in the lifespan and the impact is negligible compared to the operation phases (Jiang et al., 2021).

Under the system boundaries, it is important to analyze the context or the specific industry (type of OW) in which LCA was conducted. Table 1 further includes the type of OW. Municipal OW includes the organic fraction of municipal solid waste (OFMSW), yard waste (YW), and food waste (FW). Diary and Livestock waste mainly included cow manure, pig manure, pig slurry, poultry litter, returned dairy products, slaughterhouse waste, and fish leftovers. Most of the studies had considered more than one OW type into their LCA as the substrate which is defined as co-digestion rather than considering one type of waste as the substrate which is mono digestion (Esteves et al., 2019). Under agricultural food waste, previous studies were done on fruit waste (pineapple, apple peelings), vegetables (cucumber waste, pumpkin peelings), and sugar cane scum (González et al., 2020; Li et al., 2021; Somorin et al., 2023). It is critical to understand that depending on the type of waste, the scope considered under the system boundary of the LCA has significantly varied. LCA studies done for the industrial sector focused on the AD plants attached to a farm or a factory (Adghim et al., 2020; Lin et al., 2021; Mendieta et al., 2021; Shih et al., 2023). If such a farm selected the cradle-to-grave system boundary, the waste collection and transportation are not included in the scope because the AD plant is attached to the farm itself. However, if the main product of the AD, biogas, is intended to be used as a vehicle fuel after upgrading, then a transportation phase will come in the process. In this way, a huge inconsistency in the system boundary was observed which hinders the comparability of the results. This emphasizes the urgency of developing PCRs in this area.

3.2. Life Cycle Inventory Analysis (LCI)

The second step in the standard LCA is the life cycle inventory analysis (LCI). This phase involves data collection regarding the amount of labor, time, pollutants, environmental emissions, and production of energy (Sridhar et al., 2021). The accuracy of this data directly affects the results of the LCA study (Esteves et al., 2019).

3.2.1. Data Sources

When selecting data sources for the LCA, a hierarchy should be followed. As an example, if a specific industrial scenario is considered, the data relevant to that industry should be collected (for example: Farm/Plant). After carefully investigating the past LCAs, several researchers also followed this hierarchy and tried to collect situation-specific data (Mancini et al., 2019; O'Connor et al., 2020; Orner et al., 2022; Shih et al., 2023; Shinde et al., 2021). The next stage of the data collection hierarchy is to refer to the previous similar local studies done and national statistics. If data is not available, researchers tend to use databases and literature data. With the use of generic databases and literature data, the uncertainty in LCA results increases. For example, the Ecoinvent database focuses on the

European region. and using that database in other parts of the world may not reflect the local viewpoints on the environmental impacts (Esteves et al., 2019). However, as per the literature review results, most researchers incorporated a combined approach by mainly relying on a database while using case-specific data, and literature-based data also for their LCI.

According to the detailed results shown in Table 2, Ecoinvent is the most popular database among the LCA research studies. Different versions of Ecoinvent have been used in 28 research studies. Even though 13 papers have used Ecoinvent as their only source of data, five have been done outside of Europe (Adghim et al., 2020; Balcioglu et al., 2022; Li et al., 2021; Panigrahi et al., 2022; J. Wang et al., 2021). Several other LCA studies have used GREET as a database. GREET database is specific to the emissions and energy consumption of the transportation sector in the USA (Miller & Theis, 2006). All those identified studies focus on USA cases (Nyitrai et al., 2023; Sahoo & Mani, 2019; Y. Wang et al., 2023). Sahoo & Mani (2019) used the USLCI database that was developed by the National Renewable Energy Laboratory for their LCA (Sahoo & Mani, 2019). USLCI is a LCA database developed specifically focusing on the USA.

Table 2. presents further details about the databases used in each LCA study separately.

3.3. Life Cycle Impacts Assessment (LCIA)

Life Cycle Impacts Assessment is the third step in LCA (International Organization for Standardization, 2006). According to the studies investigated, there were various LCIA methodologies used by previous researchers. ReCipe, CML, IMPACT, and IPCC are the most used methods among the reviewed studies.

Table 2 contains the LCIA method used in the reviewed LCA studies. It shows that the ReCipe method has been frequently used to quantify environmental impacts. In fact, out of 46 reviewed articles, 18 have used the ReCipe method: mostly the ReCipe mid-point. Only 6 of them considered end-point results as well. Previous literature reviews that focused on LCAs done before 2020, showed that the CML method was the most popular impact assessment method among researchers (Dastjerdi et al., 2021b; Esteves et al., 2019).

Table 2. Different LCIA methods and the databases used.

No	Study	LCIA method							Used Database
		ReCipe	CML	IPCC	IMPACT world+	Environmental Footprint	USEPA, JRC, EPS	Not mentioned	
1	**(Demichelis et al., 2022)**	✓							Ecoinvent
2	(Pasciucco et al., 2023)	✓							Ecoinvent
3	(van den Oever et al., 2021)	✓							Ecoinvent/ Doka
4	(Mayer et al., 2021)	✓							Ecoinvent
5	(Mayer et al., 2020)	✓							Ecoinvent/ Experiments
6	(X. Zhou et al., 2022)	✓							Ecoinvent

7	(Lin et al., 2021)	✓		Ecoinvent/ Case-Specific
8	(Gálvez-Martos et al., 2021)	✓		Not mentioned
9	(Weligama Thuppahige & Babel, 2022)	✓		Ecoinvent
10	(Mendieta et al., 2021)	✓		Case-Specific
11	(Mancini et al., 2019)	✓		Ecoinvent
12	(Somorin et al., 2023)	✓		Aspen PLUS
13	(Panigrahi et al., 2022)	✓		Ecoinvent
14	(Balcioglu et al., 2022)	✓		Ecoinvent
15	(Bacenetti et al., 2019)	✓		Ecoinvent
16	(Valenti et al., 2020)	✓		Ecoinvent
17	(Shih et al., 2023)	✓		Ecoinvent
18	(Gadaleta et al., 2023)	✓		Ecoinvent
19	(Adghim et al., 2020)		✓	Ecoinvent
20	(Shinde et al., 2021)		✓	Case-Specific
21	(Gupta et al., 2022)		✓	GaBi / Past Literature
22	(Li et al., 2021)		✓	GaBi
23	(Francini et al., 2019)		✓	Ecoinvent

24	(Jiang et al., 2021)	✓					Ecoinvent
25	(H. Zhou et al., 2022)	✓					Ecoinvent
26	(Castellani et al., 2023)	✓					WRATE
27	(González et al., 2020)	✓					Ecoinvent
28	(Vinitskaia et al., 2021)	✓					Past Literature/ GaBi
29	(S. Chen et al., 2023)	✓					Past Literature/ Field data
30	(S. Wang et al., 2021)		✓				NREL
31	(Nyitrai et al., 2023)		✓				IPCC / GREET
32	(D. Wang et al., 2020)		✓				IPCC
33	(Sardarmehni & Levis, 2021)		✓				Ecoinvent
34	(R. Chen et al., 2022)		✓				Ecoinvent
35	(Sahoo & Mani, 2019)		✓				USLCI/ GTREET
36	(Tominac et al., 2021)		✓				EPA Data
37	(Behrooznia et al., 2020)			✓			Ecoinvent
38	(Arfelli et al., 2023)			✓			Ecoinvent
39	(van den Oever et al., 2021)				✓		Ecoinvent
40	(Guillaume et al., 2023)				✓		GaBi
41	(Zhen et al., 2023)					✓	IPCC
42	(Y. Wang et al., 2023)					✓	Ecoinvent/ GREET

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43	(Lee et al., 2020)	✓	Doka
44	(J. Wang et al., 2021)	✓	Ecoinvent
45	(Nordahl et al., 2020)	✓	Ecoinvent
46	(Orner et al., 2022)	✓	Case-Specific

Another significant aspect of LCIA is the quantified damage categories. There are 18 different ICs (mid-point) used in the reviewed research papers. Only 6 of the reviewed papers contained the environmental impact results for all the 18 damage categories or ICs (Arfelli et al., 2023; Balcioglu et al., 2022; Mancini et al., 2019; Panigrahi et al., 2022; Shih et al., 2023; Somorin et al., 2023). Among those 18 ICs, Global Warming Potential (GWP) was quantified in almost all the reviewed LCA studies except one. The exception was Zhen et al. (2023) where environmental impacts were evaluated by using the EPS method that included impact categories such as life expectancy, severe morbidity, morbidity, severe nuisance, nuisance, crop growth rate, wood growth rate, fish and meat production, soil acidification, depletion of reserves, and species extinction (Zhen et al., 2023). This EPS Model is also not widely used: it only evaluates the economic value of the environmental burdens. They represented the environmental burden using monetary values that no other study had done. However, GWP is the more focused damage category among the researchers because climate change and global temperature increase are the major issues addressed by implementing AD for OW management. At the same time, the global commitments to reducing greenhouse gases (GHG) might have impacted this high tendency of considering GWP in the LCA studies. The other reason is that GWP is an internationally standardized assessment, which does not require regional characterizations with lower uncertainty compared to the other ICs (Dastjerdi et al., 2021b). Apart from GWP, Eutrophication, Acidification, Human Toxicity, and Ecotoxicity are the other most popular ICs considered in the reviewed articles occurring at 32%, 28%, 20%, and 20% respectively.

3.3.2. The Use of LCA Software

There are many LCA software packages available to quantify the environmental impacts, analyze results using sensitivity analysis, and undertake Monte Carlo simulations efficiently. These software packages can be identified as classical software and waste management-specific software (Mayer et al., 2019). Software such as SimaPro, OpenLCA, and GaBi are classical software that are not specifically developed focusing on waste management applications. Conversely, there are software such as EASETECH and WRATE that are focused on waste management sector LCAs.

According to the observations, different versions of SimaPro are the most common software used which accounts for 51% followed by GaBi and OpenLCA with percentages of 19% and 11% respectively. However, 11 LCA studies did not reveal the software used. There were several LCA studies done using software that was designed specifically for waste management related LCA studies. Somorin et al. (2023) used EASETECH in their LCA analysis that was focused on AD of agricultural FW (Somorin et al., 2023). Castellani et al. (2023) used a different software called WRATE in their LCA that focused on municipal OW management in remote islands of Italy (Castellani et al., 2023). Sararmehni & Levis (2021) calculated the environmental impact quantities of MSW treatment methods in the USA by using a modern software called SWOLF (Solid Waste Optimization Lifecycle Framework) (Sardarmehni & Levis, 2021). Using different software packages gives you different results according to the different calculation methods and parameters used in that software that again caused the inconsistency in LCAs on AD which again caused to the incomparability of the results.

3.3.3. Scenario Comparisons Used

Most of the reviewed studies have used LCA to compare different scenarios. Weligama Thuppahige (2022) conducted a descriptive LCA focusing on one existing AD facility in Sri Lanka

(Weligama Thuppahige & Babel, 2022). All the other studies compared a couple of scenarios in their assessment. Some of the change-oriented-mode LCAs can be divided into 3 categories.

Focusing AD Parameters:

Several researchers performed their LCA studies considering only the AD process. Demichelis et al. (2022) investigated the AD of organic fraction of municipal solid waste (OFMSW) by analyzing 18 different scenarios by varying AD parameters that influence the environmental impacts of the AD (Demichelis et al., 2022). The 18 scenarios were generated by combining 3 incubation periods, 3 S: I ratios, and 2 types of inoculums. Li et al. (2021) conducted a similar LCA for AD of dairy manure and cucumber waste (ratio 1:1) (Li et al., 2021). They changed the solid content (Total Solid – TS) of the substrate and generated 3 scenarios: Liquid, Semi-Solid, and Solid.

Balcioglu et al. (2022) contributed by evaluating the environmental impacts of AD on waste generated in the livestock industry in Turkey (Balcioglu et al., 2022). They combined feedstocks such as cattle slurry, chicken manure, slaughterhouse waste, vegetable waste, and maize silage and came up with 4 scenarios to conduct their LCA.

Another study was conducted to evaluate the environmental impacts by varying the proportion of biogas utilization methods (Pasciucco et al., 2023). The four scenarios analyzed are 100% of the produced gas used in the internal combustion engine (ICE) to generate combined heat & power (CHP), 81% of produced gas upgraded to biomethane + 19% used for CHP in ICE, 90% of produced gas upgraded to biomethane + 10% CHP in ICE, 100% of produced gas upgraded to biomethane. Shinde et al. (2021) also investigated 2 similar scenarios for the AD of OW (Shinde et al., 2021). Using produced biogas as a vehicle fuel for the public buses after upgrading and using biogas for electricity generation to use in electric buses are the 2 scenarios compared in that LCA. Gonzales et al. (2020) added another research outcome to this category by evaluating 2 scenarios by varying the method of biogas utilization. That study was done targeting the AD of fruit and vegetable waste. Using biogas in a CHP unit to generate heat and electricity and upgrading biogas to use as vehicle fuel are the 2 scenarios that they investigated (González et al., 2020). A study conducted in the UK on AD of cow slurry and FW compared the impacts of 4 scenarios for different biogas upgrading technologies. Pressurized waste scrubbing, chemical scrubbing, membrane separation, and pressure swing adsorption are the four upgraded technologies (Gupta et al., 2022). According to these findings, it is challenging to define realistic scenarios due to many variables that can impact on the LCA results of AD, assessing the sensitivity of these identified parameters, and generalization of the results. Also, the results associated with these results depend on the waste management policies, regulatory frameworks, and energy mix which make it difficult to generalize the findings.

Comparing AD with Other Methods:

Some scenarios considered in previous research compared the environmental impacts of AD with other alternative OW treatment methods. Researchers compared the fluctuation in environmental impacts of the existing waste treatment process, after introducing AD to treat the OW. Combined or cascaded treatment options are not considered here. Ten LCA studies identified under this scenario comparison are summarized in Table 3.

Nyitrai et al. (2023) analyzed and compared treatment options for food waste and sewage sludge in the USA (Nyitrai et al., 2023). Under this study, landfill, composting, waste to energy, conventional AD, and novel two-phase AD were compared in terms of their environmental impacts. Zhour et al. (2022) compared co-digestion, co-gasification, co-combustion, incineration, and landfilling of sewage sludge in China (X. Zhou et al., 2022). Mendieta et al. (2021) studied the improvement in the environmental impacts of introducing AD to treat agricultural crop residues that were previously open-burnt (Mendieta et al., 2021). Behrooznia et al. (2020) compared the conventional composting of MSW in Rasht Iran, with AD (Behrooznia et al., 2020). Another study was conducted to evaluate and compare the environmental impacts of conventional wastewater treatment and AD-based modern technology called Smart Green Electricity Product Module (SGEPM) to swine farm wastewater treatment in Taiwan (Shih et al., 2023).

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When comparing AD with other treatment pathways, precise system boundaries and consistent assumption are important. Differing technology matuarity levels, geographical location, and feedstock characteristics will increase the complexity while leading to conflicting results finally.

Cascaded Treatment:

Another group of scenario comparisons identified was the use of multiple treatment options in the cascading method. As an example, Mayer et al. (2021) considered 5 scenarios by combining AD, incineration (I), composting (Comp), and hydrothermal carbonization (HTC) as "Option I", "Option AD+Comp", "Option AD+I", "Option HTC+I", and "Option AD+HTC+I" (Mayer et al., 2021). Here, "Option AD+I" evaluated the environmental impacts of AD on OW followed by incinerating the by-product: digestate. Similarly, in the last alternative "Option AD+HTC+I", the substrate first undergoes AD, then solid digestate is treated in an HTC plant, and the by-product of the HTC plant (Hydro-char) is incinerated in an incinerator. J. Wang et al. (2021) conducted their LCA following a similar scenario comparison by combining AD with Py for OFMSW in China (J. Wang et al., 2021). Four scenarios that they analyzed were "S1: AD", "S2: Py", "S3: AD+Py", and "S4: Py+AD". Another study was done under this cascaded treatment concept, by combining AD, Comp, and I for the OFMSW in Germany (Mayer et al., 2020). Four scenarios were analyzed and were "AD+Comp", "I", "Drying+I", and "AD+I". As in the previous LCA studies, the "AD+Comp" scenario considered AD of OFMSW followed by composting of resultant digestate.

According to these findings, past LCA studies have investigated the environmental impacts by mainly introducing an alternative option for the resultant digestate of AD which is the by-product of AD. Also, several studies did not consider all the combinations that can be formed by the selected alternative treatment options. Other than that, no other type of LCA investigation on cascaded treatment was found. LCA studies on applicable improvements to the OW before AD have been done very rarely. Without having a comprehensive set of scenarios to reflect all practical combinations, a holistic understanding of the cascaded treatment cannot be achieved.

3.4. LCA Results Interpretation

There were several studies conducted by varying the AD parameters and analyzing the environmental impacts of the AD process that were introduced in section 3.3.3 section. In that study, the main impact parameters for the AD: incubation time, S: I, and inoculum type were varied and checked for the resultant environmental impacts (Demichelis et al., 2022). They analyzed 18 scenarios for 0d, 5d, and 10d as the incubation times, 1:2, 1:1, and 2:1 as the S: I ratios, and waste-activated sludge and cow agricultural sludge as the inoculum types. In the end, they concluded that increasing the incubation time and the S: I ratio with both the inoculum types reduced the environmental impacts of the AD of OW. Even though they quantified the results in 7 ICs at the mid-point level, climate change was considered by specifically emphasizing that it was selected because it is the most studied category in the past literature (Demichelis et al., 2022). Li et al. (2021) analyzed the impact of TS content in agricultural waste (cucumber waste and dairy manure) on the AD process (Li et al., 2021). After analyzing 3 scenarios, they concluded that increasing the TS from 6% to 22% could enhance the methane yield and digestate nutrient level resulting in better environmental impacts. Another significant outcome from their research is that increasing the TS up to 25% causes to reduction in the CH_4 yield by 20% which leads to a decrease in the overall environmental credits.

The effect of the type of waste on the LCA results was evaluated in Turkey in 2022 (Balcioglu et al., 2022). This study revealed that using only cattle slurry as the substrate gives the worst environmental impact while the mix of chicken manure, vegetable waste, slaughterhouse waste, and cattle slurry gives better results in terms of GWP (Balcioglu et al., 2022).

Both Gonzalez et al. (2020) and Shinde et al. (2021) evaluated the environmental impacts by comparing the use of biogas as a vehicle fuel and the use of biogas to generate electricity (González et al., 2020; Shinde et al., 2021). Using produced biogas in an internal CHP unit and generating electricity was concluded by both research teams as the most environmentally friendly option rather than upgrading the biogas to vehicle fuel. Both were done in a European context using the same CML LCIA method. However, Pasciucco et al. (2023) came up with a contradictory conclusion to the other

2 studies (Pasciucco et al., 2023). According to his LCA results, the scenario of using 100% produced biogas to generate CHP in an internal combustion engine (ICE) shows the worst environmental results in terms of GWP, Ozone Depletion, and Abiotic Fossil Depletion. Among them, GWP shows the worst results compared to the other ICs. The best results were with the scenario of using 81% of biogas to upgrade to biomethane and 19% of biogas combust in ICE to generate CHP. Pasciucco et al. (2023) considered chemical absorption as the method of biogas upgrading while both other studies considered water scrubbing as the method of upgrading (Pasciucco et al., 2023). Furthermore, Pasciucco et al. (2023) mentioned that water consumption for chemical absorption is 0.12kg water/Nm^3 biogas while Gonzalez et al. (2020) mentioned the water consumption as 4kg water/Nm^3 biogas which can be identified as a major reason for this contradictory conclusion (González et al., 2020; Pasciucco et al., 2023).

3.4.1. Comparing AD with Other Methods:

Table 3 shows how AD has been compared as an alternative organic waste treatment method in the reviewed literature. 80% of the LCAs concluded that anaerobic digestion is the option to treat OW with minimum environmental burdens. Zhou et al. (2022) demonstrated that an optional method called Co-gasification is the best option over AD (X. Zhou et al., 2022). In Co-gasification OW is placed in a gasification system and produces syngas as the main product and biochar, residues as the by-products (X. Zhou et al., 2022). Nordahl et al. (2020) also concluded their LCA with a contradictory finding which proved that composting raw OW was the best solution over AD in terms of GHG emissions (Nordahl et al., 2020). However, they arrived at this conclusion by analyzing only the GHG emission results and no other mid-point ICs. Overall, according to these literature survey data, it is reasonable to conclude that AD is the most environmentally friendly OW diversion method.

Table 3. Summary of comparison results of AD with other methods.

Feedstock Material	Country	Comparing AD with	Preferred alternative	Reference
FW, YW, Biosolids	USA	Landfilling with the use of LFG Landfilling without using LFG. Composting	HS-AcD (High Solid Anaerobic Co-digestion)	(Lee et al., 2020)
SS, FW	USA	Landfilling Composting Waste to Energy	Novel two-phase AD	(Nyitrai et al., 2023)
CM, feed waste, SS, Returned dairy products	Dubai	Landfilling	AD	(Adghim et al., 2020)
SS, WW, FW, Used oil	China	Landfilling Incineration Co-combustion Co-gasification	Co-gasification	(X. Zhou et al., 2022)
ACR, SCS	Columbia	Discharging to water after open burning	AD	(Mendieta et al., 2021)
OFMSW	Iran	Composting	AD	(Behrooznia et al., 2020)
OFMSW	Italy	Landfilling	AD	(Castellani et al., 2023)
Municipal OW (Mainly FW)	USA	Composting Landfilling	Composting	(Nordahl et al., 2020)

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FW, YW	USA	Composting Landfilling	AD	(Tominac et al., 2021)
CM, Grass	Ireland	Landfilling	AD	(O'Connor et al., 2020)

3.4.2. Sensitivity Analysis:

Sensitivity Analysis is important in life cycle results interpretation even though it is not defined in the ISO standards as an essential step. In a sensitivity analysis, selected parameters that impact the LCA results are varied by a pre-defined value to determine their impact on the outcomes. Of 46 reviewed articles, 20 articles did not conduct a sensitivity analysis. The rest conduct a sensitivity analysis by varying different parameters. Methane yield or specific gas production is the most used parameter for the sensitivity analysis among the reviewed articles (Adghim et al., 2020; Francini et al., 2019; Gupta et al., 2022; Sahoo & Mani, 2019; Somorin et al., 2023; X. Zhou et al., 2022). From the sensitivity analysis of Adghim et al. (2021), methane yield was identified as a less impactful parameter for several ICs (Adghim et al., 2020). The sensitivity analysis done for the LCA results for AD of agricultural food waste in Uganda introduced methane yield as the most impactful parameter for GWP (Somorin et al., 2023). 10% variation of methane yield accounts for 11% and 8.5% impacts on GWP in 2 scenarios under their study.

The second most utilized parameter was the transportation distance from the waste generation point or central waste collection hub to the treatment plant which was observed in 5 LCA studies (Behrooznia et al., 2020; Demichelis et al., 2022; Jiang et al., 2021; Mendieta et al., 2021; Shinde et al., 2021). Mendieta et al. (2021) conducted a sensitivity analysis by changing the firewood transportation distance from 20km to 50km and 80km and evaluated the impacts (Mendieta et al., 2021). As per their analysis, the ozone depletion category was the highly sensitive IC for this transportation distance. It showed a 7.3% increase when the distance increased to 80km from 20km. After reviewing another study done in Ireland, it was highlighted that the most sensitive ICs for transportation are GWP, FDP, and HTP (Jiang et al., 2021). They changed the transportation distance from 10km to 4.2km and 26.7km. GWP, FDP, and HTP showed variations of -3%, -2%, -3% for 4.2km, and +10%, +5%, +39% for 26.7km respectively. Behrooznia et al. (2020) also identified transportation distance affects the overall environmental impacts of the AD system considerably (Behrooznia et al., 2020). Energy consumption in different sub-processes in the treatment system was also considered by several researchers in their sensitivity analysis (R. Chen et al., 2022; Lin et al., 2021; H. Zhou et al., 2022).

The selection of sensitivity parameters, highly concentrated around a couple of parameters such as methane yield and transportation distance which cause to overlook the influential parameters such as digestate management and system boundary assumptions. Identifying and prioritizing the most influential parameters is important to have a representative sensitivity analysis. Also, defining the range of variation should also be consistent because some have varied the transportation based on context specific data and others have just used arbitrary ranges leading to skewed results.

3.4.3. Uncertainty Analysis:

The purpose of an uncertainty analysis is to account for the uncertainties in the data used which differs from the purpose of the previously discussed sensitivity analysis. Uncertainty in LCI data affects the results of the LCA. Even though many LCA studies have conducted a sensitivity analysis to see the variation in the results according to the input parameter variations, only a few studies (13%) accounted for the uncertainty of the data. Most of those studies performed Monte Carlo analysis with 10,000 simulations to conduct this uncertainty analysis (Arfelli et al., 2023; Mayer et al., 2020; Nyitrai et al., 2023; van den Oever et al., 2021; X. Zhou et al., 2022). Nyitrai et al. (2023) performed a comprehensive uncertainty analysis by selecting many parameters such as digester solids feed (%), digester methane yield, biogas capture efficiency, heat output (%), distance to landfill (km), and LFG utilization (%) and presented the midpoint impact results in a range with 95% confidence level (Nyitrai et al., 2023). Also, several studies have incorporated the pedigree matrix to determine the indicator scores for parameters considered in the uncertainty analysis (Arfelli et al., 2023; Mayer et al., 2020; van den Oever et al., 2021). Some of the LCA studies were conducted with a Monte Carlo analysis with 10,000 simulations to account for the LCC results under their economic assessment (Francini et al., 2019; Lee et al., 2020; Mayer et al., 2021).

3.4.4. Contribution Analysis:

Another highlighted feature under the LCA results interpretation is the contribution analysis that presents the midpoint or endpoint ICs according to the phase-wise contribution. Even though many researchers performed the process-wise (phase-wise) contribution analysis, some have performed it from an elementary flow perspective (Arfelli et al., 2023). However, most of the reviewed LCA studies (74%) have presented the results after conducting a contribution analysis. While all other studies performed the contribution analysis focusing on the midpoint or endpoint ICs, Sahoo et al. (2019) conducted it for the energy usage and GHG emissions of the whole supply chain of BioCNG which is the main product in that study (Sahoo & Mani, 2019).

3.4.5. Inventory Analysis:

Almost every LCA study has conducted an inventory analysis. Some have presented it in the paper itself to a certain level while most others have presented it as supplementary material of the publication. Among reviewed 46 reviewed articles, only 7 have not conducted an inventory analysis.

4. Discussion

The previous LCA research on AD was done mainly with the goals of decision-making and learning or exploration. Under decision-making, most LCA studies have focused on policymaking in municipal waste management and industry sector waste management in the countries. Under learning/exploration, the goal was to identify the improvement opportunities for the existing treatment methods.

Even though past review studies revealed that many LCA studies had been conducted without following the ISO standards, this review study proved that the trend has changed and the latest LCA studies comply with the ISO 14040 standards (Mayer et al., 2019). Almost every LCA study has defined a functional unit and the considered system boundary in the LCA. In recent LCA studies on AD of OW, feedstock amount-based (unitary and fixed amount) functional units are the most frequently used ones. The cradle-to-grave system boundary is the most popular boundary condition among the researchers in this knowledge domain.

According to the literature review results, several apparent knowledge gaps should be addressed. One of the rarely investigated areas is the LCA of biogas upgrading methods. Assessments focusing on biogas (A mix of CH_4, CO_2, SO_2, and H_2O vapor) to vehicle fuel or BioCNG upgrading methods was found in only one article among the reviewed articles (Gupta et al., 2022). Several other researchers concluded that upgrading biogas to vehicle fuel is less environmentally friendly without mentioning the exact method of upgrading (Shinde et al., 2021). They compared the option of electricity/heat generation using an in-house CHP unit and the option of upgrading biogas (Shinde et al., 2021). Gonzalez et al. (2020) concluded heat/electricity generation is the best option compared to the biogas upgrading option (González et al., 2020). Hence, future LCA studies in this area should focus on biogas upgrading/purification methods as well.

Another key observation is that most of the LCA studies compared AD with conventional methods such as landfilling, composting, and incineration. Most of these studies have revealed AD as the environmentally preferred option compared to conventional methods. However, several studies have identified co-gasification as the best option after assessing the negative impacts on all the ICs when compared with the other methods such as AD, landfilling, and incineration. Hence, it is important to compare AD with options such as co-gasification to understand better OW treatment methods.

The lack of proper PCRs in LCA of AD was highlighted as one major reason for the inconsistency of LCA results. Hence, it is important to focus on the development of PCRs in future research studies to increase comparability, transparency, and accuracy.

Sensitivity analyses were conducted by varying one parameter at a time. They have considered selected parameters that affect the final LCA results logically. As explained in a previous section, methane yield, waste transportation distance and energy consumption in various unit processes are the most considered parameters for the sensitivity analysis by past researchers. However, the evaluation of the combined effect of more than one parameter was not found in any reviewed article. As an example, varying the transportation distance by (+/-) 20% has a certain impact on the final ICs. Varying the methane yield by (+/-) 20% also has an impact on the final ICs. If both the transportation distance and the methane yield varied at the same time by (+/-) 20%, they should impact the final ICs in a whole different way. This has been overlooked in the articles reviewed.

Also, there is a potential to extend these LCA studies on AD to calculate the potential carbon credits under different carbon credit-based guidelines such as Clean Fuel Regulation in Canada and Low Carbon Fuel Standards in California (Canada. Environment and Climate Change Canada, 2023; Witcover et al., 2022). Then it will increase the economic value of AD of OW and it will attract more attention from different stakeholders such as municipalities, other industries, and researchers towards AD and its further improvements.

Finally, multiple organizations and institutions have adopted the United Nations Sustainable Development Goals (UNSDGs) to guide their efforts towards sustainability. Identifying and evaluating environmental impacts is an important aspect when assessing the performance of AD in meeting the UNSDGs (Piadeh et al., 2024). The contribution from AD directly affects the achievement of several SDGs. SDG 11 (Sustainable cities and communities), SDG 7 (Affordable and clean energy), SDG 12 (Responsible production and consumption), and SDG 13 (Climate action) are directly affected by AD. LCA is a scientific method to evaluate the measurement of environmental impacts of AD under different impact categories. The results of those evaluations can justify the level of achievement of each SDG. Hence, LCAs assessing AD indirectly helps to achieve the UNSDGs in the long run.

5. Conclusion

This paper reviewed the latest LCA studies conducted specifically on the AD of OW to address noted research gaps. 46 journal articles from 2019 to 2023 were reviewed and investigated. All of those are LCA studies focusing on the AD of different OW types in different parts of the world. This paper investigated the LCA aspects to identify the significant trends, challenges, and issues. Because of that, this paper was structured according to the four main steps of LCA as defined by ISO standards. The results of the reviewed articles were summarized under each of those steps. Under the goal and scope definition stage, review results of FUs, and system boundaries were mainly discussed. Used databases were mainly summarized under the LCI stage. Impact assessment methods and software packages were explained under the LCIA step. Under the last step of standard LCA, the life cycle interpretation step explains the important results of those LCA studies.

None of the LCA studies are identical to each other, and as a result, it is challenging to compare two LCA studies by only reviewing their final impact values. There are many factors such as FU, system boundary, referred database, utilized software, and following an LCIA method that impact the comparability of LCA studies. Maintaining the consistency of LCAs on AD is challenging without having PCRs. Regardless, AD appears as the alternative OW diversion strategy with the least environmental burdens compared to most of the other options available in the literature.

It is recommended to extend the research in this research domain to address the knowledge gaps in the discussion section which are about the biogas upgrading methods, comparing AD with the latest treatment options, and carbon credit-based assessments. The lack of sophisticated studies focusing on social sustainability of AD, combined with inconsistent approaches in most of the steps in LCA, sensitivity analysis, and allocation strategies emphasize the significant challenges in this research domain. Addressing these challenges is crucial for having a better understanding of AD systems, ensuring future studies can consider all three pillars of sustainability: environmental, economic, and social dimensions. Prioritizing research to capture these underexplored areas and paying attention to the methodological inconsistencies will be important to achieve more reliable and generalized LCA outcomes.

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