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Review

A Review of Life Cycle Assessment Application in Municipal Waste Management: Recent Advances, Limitations, and Solutions

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Abstract: The treatment or utilization of municipal solid waste (MSW) is a topic of intense global concern. Life cycle assessment (LCA), as applied to municipal waste, has recently attracted significant attention from researchers. The life cycle of MSW encompasses a series of processes, beginning with waste generation and ending with its final disposal. This study aims to provide an overview of the LCA methodology and the development of various software tools, discussing both the limitations and potential of LCA. We searched the Web of Science database for all articles published between January 2003 and October 2023 on the topic of "life cycle assessment in municipal waste management". This review thus offers the most current evidence on LCA in MSW management, emphasizing the need for more effective global environmental governance to address waste management issues.

Keywords: life cycle assessment (LCA); municipal solid waste management (MSWM); sustainability; environmental impacts; LCA software

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1. Introduction

The constant growth of MSW generation and the exacerbation of its associated environmental and economic challenges are among the most pressing issues arising from contemporary socio-economic development [1]. It is clear that both population growth and significant growth in global gross domestic product (GDP) will increase the amount of waste, which constitutes a considerable threat to sustainability [2–4]. According to the World Bank, global waste generation is projected to rise from 2.01 billion tonnes in 2016 to 3.40 billion tonnes by 2050, an increase of approximately 70% [5]. The increasing quantity and complexity of the morphological composition of MSW have led humanity to realize the need to manage waste streams [6]. There is an obvious and strong link between inefficient MSW systems and environmental and wellness concerns [7]. Despite the fact that alternatives to waste management have been proposed, many countries are neglecting these, and the predominant treatment methods remain open dumping [8,9] and landfilling [10–20]. The inadequacies of traditional waste management systems, largely based on landfilling, are increasingly evident [21,22]. For example, in 2016, only 13.5% of global waste was recycled and 5.5% was composted, while a significant 40% of waste was

improperly managed [5]. Progress has provided many new possibilities and materials, resulting in a catastrophic increase in the volume of waste [23].

The inadequacies of traditional waste management systems are increasingly evident. While new technologies for waste management are being developed, their adoption and scalability face challenges. These include cost barriers, regional infrastructure differences, and uncertainty regarding their net environmental and economic benefits. To address these issues comprehensively, it is essential to evaluate the environmental and economic performance of these technologies. Here, the life cycle assessment (LCA) methodology plays a pivotal role [24,25]. By analyzing input and output flows, assessing environmental impacts, and interpreting results, LCA helps identify potential harms and inform economic, technical, and social decisions [26–29]. While it does not directly solve environmental issues, LCA provides critical data to guide effective solutions.

There are plenty of case and review studies regarding the idea of evaluating the environmental performance of waste management systems. However, they primarily concentrate on a particular type of waste or region or on specific waste treatment systems. For instance, Yadav and Samadder [30] and Othman et al. [31] analyzed LCA studies from Asian countries; some studies focused only on plastic waste [32] or on bio waste [33]; Oviedo-Ocaña et al. [34] reviewed composting systems, while Liu et al. [35] studied waste recycling. However, there is no recent review study covering LCA studies worldwide, after that conduced by Khandelwal et al. [36].

It is important for readers to understand LCA in regards to municipal solid waste management (MSWM) systems, including the development of actual technologies, the limitations, and future challenges. The purpose of this study is to provide a global overview of LCA in MSW management systems. Specifically, it aims to (1) explore the development of LCA methodologies and software tools, (2) identify limitations and future challenges, and (3) examine the environmental impacts of common MSW management practices. By synthesizing the existing knowledge and identifying gaps, this review aims to offer valuable insights that can enhance waste management practices and support the development of sustainable technologies.

2. Methodology

2.1. Literature Search Strategy

Given the extensive number of articles published on the LCA of MSWM, it is essential to critically examine these studies to provide valuable insights into scientific progress. We searched the Web of Science (www.webofscience.com, accessed on 1 January 2024) and ScienceDirect (www.sciencedirect.com, accessed on 1 January 2024) databases for articles published between January 2003 and November 2023 using the keywords "life cycle assessment", "LCA", and "municipal waste management".

2.2. Selection Criteria

The review concentrated on LCA analyses of MSWM systems, specifically addressing waste generated from residential and/or commercial (non-residential) sources. It deliberately excluded LCA studies focused on the management of construction and demolition debris, hazardous waste, medical waste, electronic waste (e-waste), and water waste. Additionally, studies that concentrated exclusively on a single type of MSWM were not considered. As a result, 109 papers that met the ISO core framework and LCA standards, published in peer-reviewed journals, were reviewed (Figure 1).

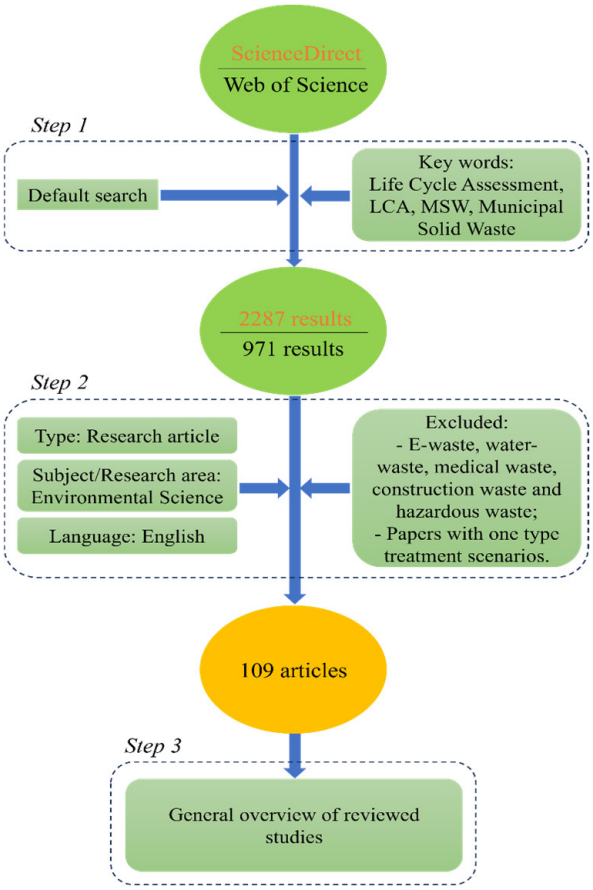


Figure 1. Search and selection criteria of LCA reviewed studies.

2.3. Review Framework

The selected studies were analyzed based on the following several key factors: (1) functional unit (FU), (2) LCA software, (3) MSWM technologies, (4) comparison of environmental impacts of landfilling (LF) and incineration (INC), and (5) the limitations and prospects of LCA in MSW.

3. Results

3.1. Geographical Distribution of LCA Studies

The geographical distribution of LCA studies provides valuable insights into the global research landscape (Figure 2). Asia leads, with 49 studies, accounting for 45.8% of the total. This prominence is attributed to the rapid industrial expansion and urbanization in countries such as China and India, which have driven the interest in assessing environmental impacts through LCA to promote sustainable practices and mitigate adverse outcomes [37]. Europe is the second most active region, conducting 35 studies, which accounts for 32.7% of the total. Meanwhile, Africa, South America, North America, and Australia/worldwide together contribute 23 studies, which is just 21.5% of the total. This collective contribution is significantly lower than that of either Asia or Europe alone.

Europe's position as the second most active region in regards to life cycle assessment (LCA) studies is driven by its strong environmental regulations, such as the EU Green Deal and Circular Economy Action Plan, which promote sustainability and life cycle evaluation. Advanced research initiatives, corporate sustainability efforts, and leadership in regards to renewable energy and green technologies further boost LCA activity. High public awareness of environmental issues and cross-border collaboration also play significant roles, making Europe a global leader in adopting and standardizing LCA practices.

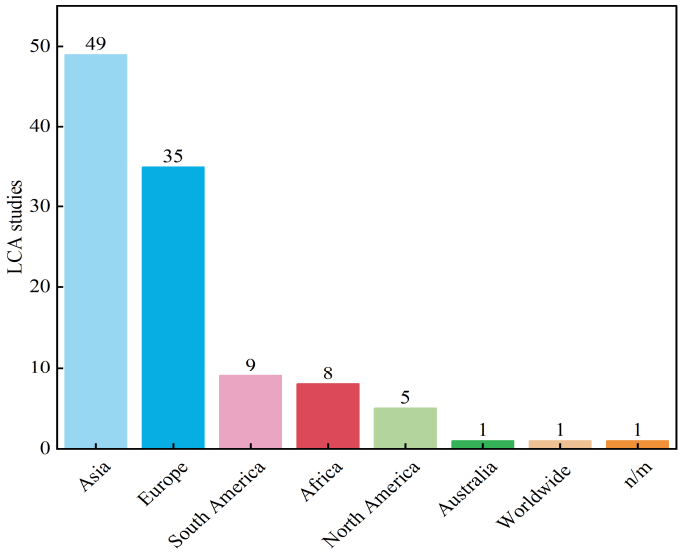


Figure 2. The allocation of LCA studies by continent. n/m—not mentioned.

3.2. Trending Topics in LCA of MSWM

Figure 3 visualizes the most frequently occurring terms in review papers on the life cycle assessment (LCA) of municipal solid waste (MSW). The size of the words reflects their prominence or frequency in the text. The largest words, such as "municipal", "waste", "management", "life cycle", and "assessment", underscore the primary focus of the review on evaluating waste management strategies using life cycle assessment methodologies. Terms like "environmental", "solid", "recycling", and "sustainability" suggest a strong emphasis on sustainable and environmentally sound waste management practices. Words like "greenhouse", "gas", and "emissions" highlight the importance of considering environmental impacts, particularly climate change. The inclusion of terms like "China", "case", and "international" points to the analysis of global or regional case studies.



Figure 3. Trending topics in LCA of MSWM.

Overall, this word cloud provides a snapshot of the review papers' content, emphasizing core topics like waste management and sustainability, while highlighting the multidisciplinary nature of the study, encompassing environmental, technological, and economic aspects.

3.3. Application and Scope of LCA in MSWM

Unfortunately, waste is often neglected in product life-cycle assessments, although in the last decade, waste management research using the LCA methodology has played an increasingly important role in selecting the most appropriate waste management solutions. The LCA of waste can be defined as a succession of processes carried out from the time the waste is generated to the time it ceases to exist. No single waste management method can ensure the fully sustainable utilization of the entire multi-component municipal solid waste stream. MSW management is an optimal combination of various waste collection, utilization, and disposal processes, e.g., collection (waste delivery system, collection at the point of generation, mobile collection points, post-component or fractional separate waste collection, or non-separated collection); material sorting and material recycling (including the production of refuse-derived fuel (RDF) briquettes); aerobic and anaerobic treatment of organic waste; thermal methods of utilization (incineration, pyrolysis, gasification); disposal (landfill disposal) [38].

The life cycle of waste is assessed in the following several stages: (1) definition of scope and system boundaries; (2) inventory of the relevant input and output flows of the waste system; (3) assessment of potential impacts on the environment; (4) interpreting the results of inventory analysis and the environmental impacts assessed in the life-cycle impact assessment (LCIA) phase.

Environmental impacts occur at all stages of technological cycles of production and consumption in waste management. The purpose of a life cycle study might be to conduct a risk assessment, environmental performance assessment, or environmental effectiveness assessment. Determination of the purpose and scope of the study consists of the principles of the case study, namely the functional unit, the system boundaries, and the selection of categories and methods of environmental impact assessment [39].

3.4. Functional Unit (FU)

A key element in defining the scope of an LCA is the selection of the object of study—the functional unit (FU) [40]. The functional unit is the unit of the product or service whose impact will be evaluated and compared. When considering waste management systems, the functional unit is the quantity of waste of a particular composition over a specified lifetime of the system under specified conditions. The review study by Khandelwal, Dhar, Thalla and Kumar [36] revealed that the most favorable FU was 1 MT.

The functional units of various LCA studies are summarized in Figure 4 and categorized into four types: unitary, generation-based, not mentioned, and others. According to results, 63% (69 of 109 LCA studies) of reviewed LCA studies considered unitary FU, such as 1 ton or 1 metric ton of MSW. Unitary FUs are normally applied in LCA studies, as the data are mostly derived from facility field visits and official government statements, where waste measurement is conducted through weighing systems at industrial facilities [41]. Unitary FUs facilitate the comparison of environmental impacts across different MSW management practices. By focusing on a single unit, calculations become more precise and straightforward. However, this approach has limitations, i.e., it does not account for the annual volume of waste generated, which can constrain its utility in long-term planning and policy making.

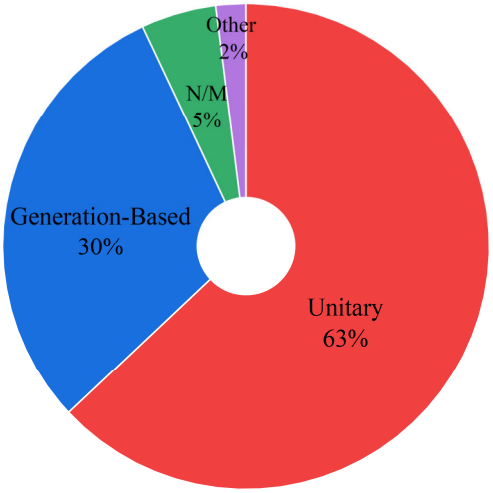


Figure 4. The allocation of the functional unit (FU) in LCA studies. N/M—not mentioned.

The second most common FU category in the reviewed studies is generation-based. Approximately 30% of the studies, equating to 33 out of 109, utilized generation-based FUs. Generation-based FUs are defined with respect to the quantity of the product or process produced. These units are particularly applicable for evaluating the environmental footprint of production operations, providing insights into resource utilization and emissions associated with manufacturing activities [42]. Generation-based FUs reflect real-time waste generation, which can aid in understanding cumulative environmental impacts. Additionally, they allow for the comparison of waste generation trends and the assessment of MSWM effectiveness. However, generation-based FUs have limitations, i.e., waste generation varies by location and other factors, making comparisons between regions or communities challenging. Moreover, they require comprehensive data on MSW generation rates, which can be difficult to collect accurately.

The other FU category comprises two LCA studies. The LCA study by Zhao, et al. [43] considered person equivalent (PE) as the functional unit. The application of "person equivalent" (PE) in LCA assumes normalization. Normalization is an LCA weighting-like step and is a non-mandatory part of LCIA [44] which facilitates the interpretation and comparison of environmental impact scores for various types of activities and technologies. Morselli, et al. [45] considered three different FUs: DALY (disability-adjusted life years) to evaluate the human health damage category, PDF (potentially disappeared fraction) to evaluate ecosystem quality, and MJ (megajoule) surplus to evaluate resource depletion. Using different FUs offers some advantages (flexibility and integrated comparison) and disadvantages (complexity and reduced comparability) [46].

The breakdown of functional units in LCA studies reflects diverse methodological approaches in defining the roles of products or processes: most studies employ unitary FUs, followed by generation-based units, with a smaller proportion either not specifying an FU or using alternative approaches. The choice between different FUs in LCA of MSWM depends on the goals of the LCA research. Unitary FUs are simpler and more straightforward for comparing. This diversity emphasizes the importance of transparently defining and justifying the choice of functional unit in LCA studies to ensure the reliability and comparability of the results.

3.5. Inventory Analysis of the Life Cycle Assessment

Inventory analysis of the life cycle assessment involves the quantification of the input parameters (energy, water, raw materials) and output parameters (emissions into the environment, e.g., air emissions, solid waste utilization, wastewater discharge) for each

stage of the life cycle of the object under study [47]. Collection, transportation, disposal, neutralization or recycling phases constitute the waste LCA. The specificity of the activities of waste management facilities is one of the most important reasons why one particular life cycle model cannot describe the development of different waste management facilities.

3.6. LCA Software

Software tools have been developed to facilitate the LCA process, supporting both the inventory analysis stage and impact assessment [48]. Software for conducting life cycle assessments of waste management systems should be flexible enough to model both typical, commonly used scenarios, as well as non-standard scenarios. The most commonly used software in this review include SimaPro (26%, Netherlands), GaBi (10%, Germany), EASETECH (5%, Denmark), and EASEWASTE (4%, Denmark) (Figure 5). A summary of their applications, benefits, and drawbacks is presented in Table 1.

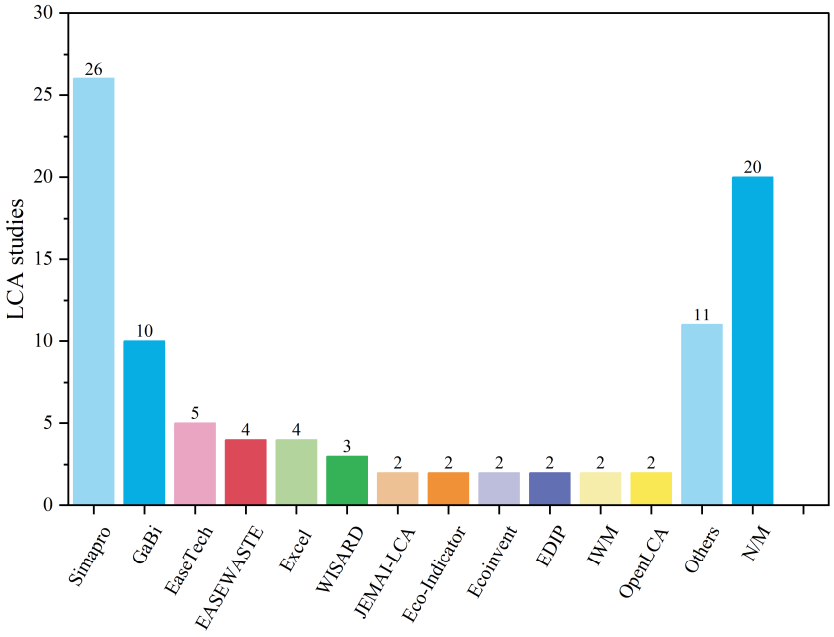


Figure 5. The allocation of LCA software in LCA studies. Others—mentioned only once; N/M—not mentioned.

SimaPro is a software product that possesses all the functions for conducting LCA. Both the process databases and impact assessment databases may be modified and augmented in unlimited ways [49]. According to the current review study, many studies used SimaPro [10,14,36,50–52]. Moreover, as significant number of case studies used SimaPro software in the life cycle analysis of municipal waste management in Turkey [53], India [54], and Pakistan [55]. SimaPro offers a wide range of features and functionalities, a user-friendly interface, integration with other software tools and databases, etc. Collectively, these studies highlight its usability in a variety of global locations and socio-economic circumstances, dealing with the challenges unique to waste management in any location. GaBi is a life cycle assessment and life cycle engineering tool that incorporates a wealth of data from industry and literature sources [56]. The user can link the dataset provided by the GaBi database with their own data to both calculate a life cycle inventory and perform an impact assessment. GaBi ranks second after SimaPro in LCA applications for waste management and has been widely used in recent research [57–59]. Both SimaPro and GaBi offer extensive and updated databases, such as Ecoinvent and GaBi's own data libraries, making them highly effective for detailed scenario analysis and environmental impact assessments. These tools provide robust support for advanced LCAs and have capabilities

for solid waste treatment processes. However, their high cost and the aggregated nature of their datasets pose challenges for certain users, particularly those looking for highly customized or specialized data for niche applications within MSWM.

Table 1. LCA software applications and their benefits and drawbacks.

No.	Abbr.	Application	Benefits	Drawbacks
1	SimaPro	Supports advanced LCA. Provides assistance in analyzing waste treatment processes such as LF, INC, REC, and COM.	Extensive and organized databases (e.g., Ecoinvent); solid scenario processing; regular updates.	High cost.
2	GaBi	Extensively used in WM for detailed modeling and analysis of waste treatment processes and their environmental impacts.	Extensive and regularly updated data libraries (e.g., Ecoinvent, GaBi databases); regular updates.	High cost; the majority of datasets aggregated.
3	EASEWASTE	Customized software for environmental appraisal of WM processes, addressing multiple methods of treatment and utilization.	Sophisticated instruments for waste management estimation; in-depth analysis of options.	Focused mainly on WM, potentially limiting broader environmental assessments; poor scale datasets compared to those of SimaPro and GaBi may limit the insight of the evaluation; less flexibility in model and process customization compared to that of more general LCA tools.
4	EASETECH	Customized software for environmental appraisal of waste management processes.	Monitors and describes mixed substance flows, thus suiting systems with heterogeneous substance flows; easily creates and modifies scenarios using new materials, processes, and effects; interoperability with other software and datasets.	Focused mainly on WM, potentially limiting broader environmental assessments; poor scale datasets compared to those of SimaPro and GaBi; necessity of sufficient and extensive data in order to ensure accuracy.
5	WISARD	Analyzes the environmental footprint of MSW treatment facilities, assessing the full waste life cycle from origin to end-of-life discharge.	Ability to consider the location of the study; provides a clear picture of environmental aspects of WM systems and is very useful in comparing various options.	Limited database and lack of data; more inflexible than other models; lack of regular updates.

EASETECH is a model developed for conducting life cycle assessments of municipal solid waste management systems. The software allows for modifications of existing databases, changes in technology and process indicators, and the creation of custom modules, along with their subsequent evaluation [60]. Several studies were performed using the EASETECH software tool [61–63]. WISARD (Waste Integrated Systems Assessment for Recovery and Disposal) is a software developed by the Ecobian group in France. The WISARD logical framework includes the production, collection, treatment, and disposal of MSW. It maintains a database with specific information concerning logistics collection, recycling, composting, incinerators, and landfills. Designed specifically for waste manage-

ment, these tools are more focused on detailed waste management assessments but have limitations in terms of broader environmental evaluations compared to those of general LCA tools. EASEWASTE and EASETECH excel in managing mixed and heterogeneous substance flows, which can be beneficial for waste management scenarios that require close monitoring and the customization of inputs. However, their limited datasets and focus on WM may reduce the flexibility and depth available in general-purpose LCA tools.

The use of various software tools creates a bias towards the environmental program, and its top priority may shift away from the original problem that lies within the company [64]. Therefore, the choice of LCA software for MSWM depends on the specific needs of the study. For comprehensive, versatile LCAs covering a wide range of environmental impacts and treatment processes, general-purpose tools like SimaPro and GaBi are preferable, albeit at a higher cost. For in-depth waste management-specific assessments that require handling of heterogeneous flows and scenario customization, tools like EASEWASTE and EASETECH are advantageous. Finally, for studies that prioritize location-specific assessments, WISARD offers tailored insights but may fall short in terms of data regularity and flexibility. As the field evolves, balancing database comprehensiveness, customization capabilities, and cost will remain critical in choosing the optimal LCA tool for MSWM.

3.7. Life Cycle Impact Assessment (LCIA)

LCIA is the process of assessing the significance of potential environmental impacts of the system under study based on inventory analysis data [65]. Methodologically, LCIA is the most complex stage of the LCA. The LCIA is made up of five elements. The first element is the identification of the impact categories (climate change, human toxicity, acidification, etc.) that best reflect the impacts of the analyzed system according to the objectives of the assessment. The second element involves classifying the results of the inventory analysis into different impact categories. The third element, characterization, involves calculating the exposure of each pollutant within a particular exposure category. The fourth element is the normalization of the calculated impact category values in relation to the available background information regarding the existing environmental load in the given region or in the country as a whole. The fifth element is weighting, which involves assessing the significance of each impact category to combine the category values into a single value that reflects the ecological characterization of the system under study [66]. The input streams in typical process cycles comprise waste of all types, and the output streams include waste processed into raw materials, or neutralized waste, etc.

3.8. Interpretation of Life Cycle Assessment Analysis

The results of the environmental impact assessment are interpreted in order to select the most favorable process or service. The interpretation phase may involve an iterative process of reviewing and updating the LCA study area and the nature and quality of the data collected, in accordance with the defined purpose [67]. The interpretation should necessarily include the selection of impact categories and categorization indicators. Based on the findings, mathematical calculations are performed to interpret the obtained results and formulate conclusions and recommendations regarding the need for adjustments in the work of the subsystem and further, the whole system of waste management, from production to consumption, in accordance with the purpose and scope of the application.

3.9. Overview of the Technologies for MSW Treatment

The continuously increasing generation of solid domestic waste, both in absolute values and per capita, along with the complication of waste composition—including the existence of more environmentally hazardous components—makes the problem of MSW generation, accumulation, and utilization management one of the priorities in ensuring the

environmental safety of the population [68]. Currently, the best utilization tools include resource-saving, low-waste, and zero-waste technologies, as well as existing technologies that contribute to environmental protection and the rational use and reproduction of natural resources, providing for the lowest possible expenditure of raw materials, energy, and other resources. The allocation of waste management options is shown in Figure 6. It should be noted, that in Figure 6a, waste management options are mentioned not only when they appear alone, but also when mixed with other options.

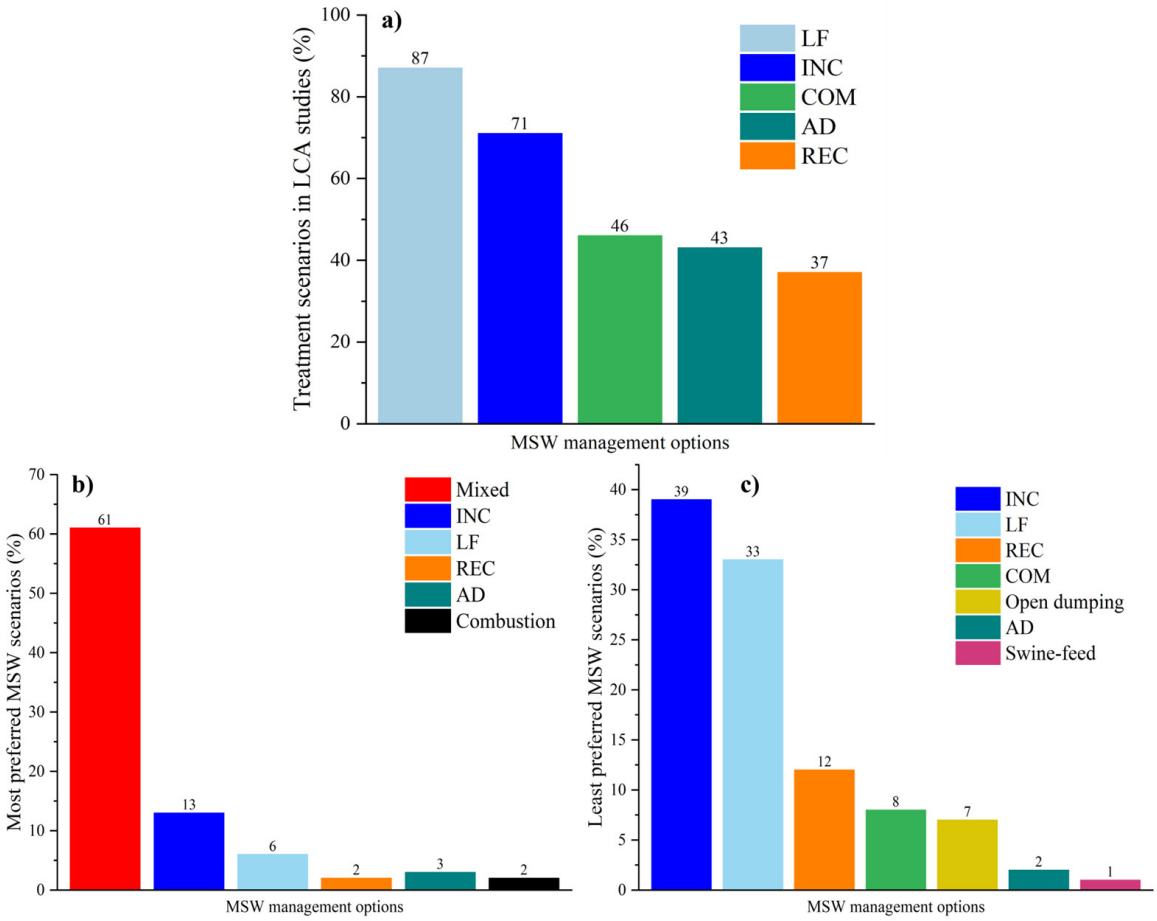


Figure 6. The allocation of MSW treatment options (**a**), most preferred options (**b**), and least preferred options (**c**). LF—landfilling; INC—incineration; COM—composting; AD—anaerobic digestion; REC—recycling.

A landfill is a complex of environmental facilities designed for the storage, isolation, and neutralization of municipal solid waste. The advantages of landfill disposal of MSW consist of the relatively low energy intensity of the process, its insignificant labor costs, and the relatively low cost of MSW disposal. However, the disadvantages of landfills include the use of large areas, which are withdrawn from use for tens of years, and the risk of environmental pollution in case of the violation of prescribed operating techniques [69]. A study by Fernández-Nava et al. [70] reported that traditional landfills have the greatest environmental impact on human health, climate change, and resource depletion. The use of the technogenic territories of landfills and dumps becomes possible only after their recultivation. The recultivation of landfills is mainly understood to consist of work on the arrangement of the surface isolation system, the creation of a fertile root-inhabited soil layer, and the restoration of living components of the biota (microorganisms, fungi, higher plants), i.e., so-called biological recultivation [71].

In recent years, LCA research has focused on wastes incineration [72–74]. Incineration is a widespread method of solid domestic waste disposal. The incineration of household waste, in addition to reducing its volume and mass, provides additional energy resources that can be used for district heating and electricity generation. Despite some advantages, incineration shows more sustainability when the waste is pre-treated, such as through the use of pre-sorting [59,74]. Incineration appears to be the least-preferred method of waste disposal (Figure 6c). The reason for this may be that in many cases, it has been compared with mixed methods, where waste sorting predominates before waste treatment [18].

In addition, the collection system is the only stage in the waste management system whose effectiveness depends on the involvement of the population [75]. The collection system is the point of contact between the population and the management system. Therefore, the introduction of separate collection should start with a system that is more convenient for the population in order to cultivate a proper attitude to waste, increasing environmental awareness and the interest of the residents in the safe disposal of waste.

3.10. Environmental Impacts of Incineration and Landfilling

Figure 7 presents a comparative analysis of the environmental impacts of two widely used waste management methods, i.e., INC and LF, using data collected from reviewed studies. While the data were collected from various studies, no comprehensive review has yet fully explained how INC and LF impact the environment across categories, such as global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), human toxicity potential (HTP), ozone layer depletion potential (ODP), photochemical ozone creation potential (POCP), abiotic depletion potential (ADP), and nutrient enrichment potential (NEP).

GWP measures the contribution of waste management processes to climate change, expressed in kg CO_2 eq. INC shows a higher median GWP (around 1.89×10^8 kg CO_2 eq), with a maximum of 5.77×10^9 kg CO_2 eq [76] and a minimum of -1.96×10^9 kg CO_2 eq [77], indicating a greater contribution to greenhouse gas emissions, mainly due to CO_2 released during combustion. However, energy recovery from incineration can offset some emissions, although the GWP varies significantly, depending on the process efficiency and waste type. LF has a lower median GWP (around 1.56×10^8 kg CO_2 eq), but methane emissions from anaerobic decomposition pose a significant risk. The study results from Vinitskaia, Zaikova, Deviatkin, Bachina and Horttanainen [17] showed the highest GWP contribution, with an emission of 4057 kt CO_2 eq. While less variable than the results from incineration, proper methane capture is crucial in reducing its impact.

Both INC and LF exhibit positive values for AP, meaning that both contribute to acid rain formation through emissions such as SO_2 and nitrogen oxides (NOx). However, LF shows a higher median AP compared to that of INC, indicating a greater overall impact on acidification. Additionally, INC exhibits more variability, with several high outliers, suggesting that its acidification impact can vary significantly depending on factors like operational efficiency and waste composition.

LF has a more significant eutrophication impact compared to that of INC, which is evident from its higher median and larger range of values. LF's higher EP is likely due to nutrient-rich leachate potentially contaminating water bodies, leading to issues like algal blooms. In contrast, INC shows a median value around -2.467 kg P eq, indicating a smaller and possibly even beneficial (negative) impact in some cases, although this may vary based on operational factors like emissions control during incineration. LF's wider range suggests more variability in its contribution to eutrophication.

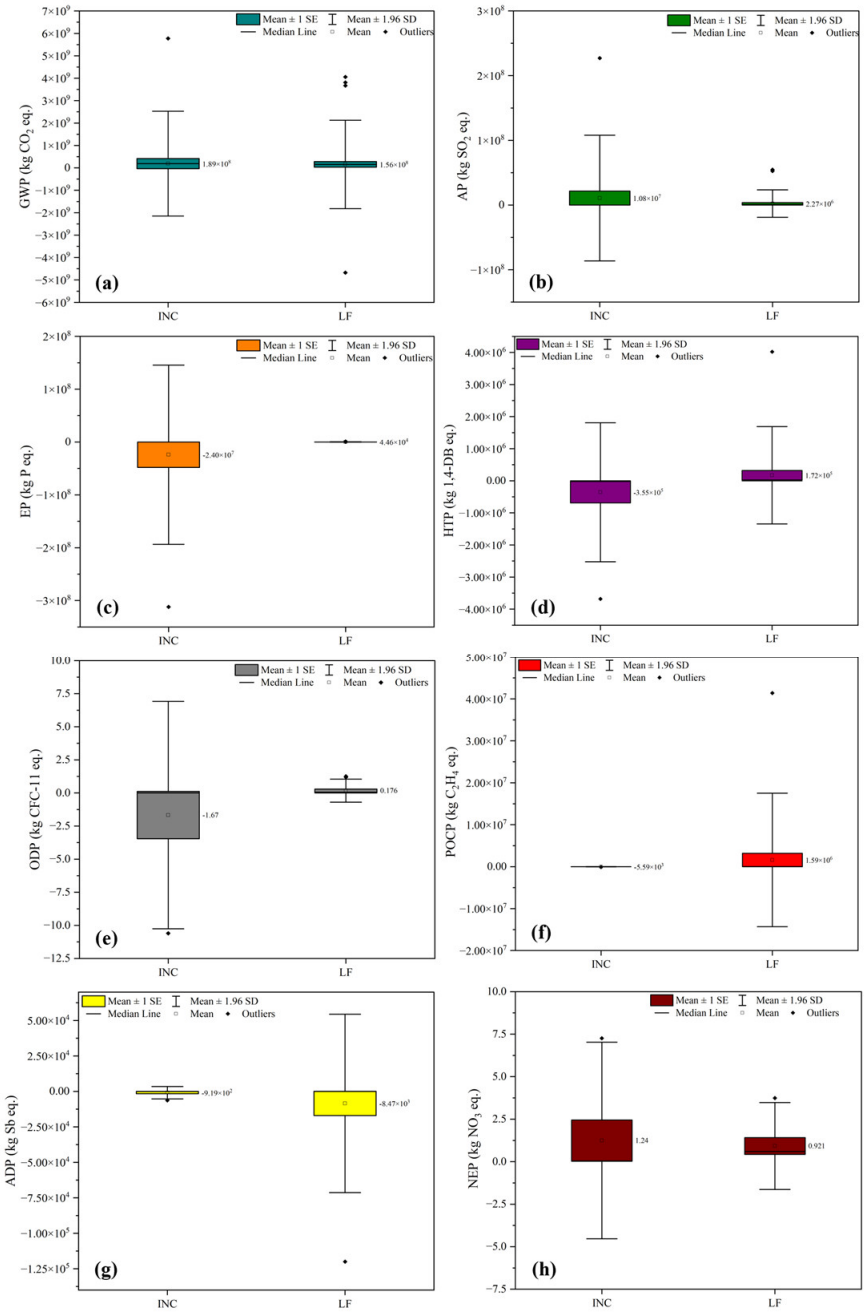


Figure 7. Ecological footprint (**a**) GWP, (**b**) AP, (**c**) EP, (**d**) HTP, (**e**) ODP, (**f**) POCP, (**g**) ADP, and (**h**) NEP.

INC shows a higher median HTP at around 3.585 × 10^5 kg 1,4-DB eq, indicating a more significant contribution to HTP due to emissions of harmful substances such as dioxins, heavy metals, and other pollutants released during combustion. LF has a lower median HTP, suggesting a reduced overall toxicity risk, but the wide range of outcomes points to variability in its impact. This variation could be influenced by factors like the effectiveness of LF gas capture systems and waste composition, which affect the release of toxic substances into the environment.

INC shows a negative median value for ODP (−1.67 kg CFC-11 eq), which suggests that INC might actually help reduce ozone depletion, potentially due to the destruction of ozone-depleting substances during combustion. In contrast, LF has a positive ODP with a smaller range of variability, indicating a consistent but positive contribution to ozone layer depletion, albeit less severe than INC's potential benefits.

INC has a negative median POCP, implying that it might help reduce the formation of ground-level ozone, also known as smog. This could be due to controlled emissions or energy recovery processes. On the other hand, LF has a positive POCP, indicating a contribution to smog formation, likely due to volatile organic compounds (VOCs) released during the decomposition of waste.

LF displays a substantial negative median ADP, indicating that it has a significant impact on the depletion of abiotic resources, possibly due to the extraction of materials required for landfill operations or infrastructure. INC, however, remains closer to neutral in ADP, meaning it has less impact on the depletion of non-renewable resources, which could be due to energy recovery offsetting resource use.

Both INC and LF show positive NEP values, indicating that both contribute to nutrient enrichment in ecosystems, which can lead to issues such as algal blooms. INC exhibits a slightly higher median, suggesting a marginally greater impact on nutrient enrichment compared to that of LF. However, INC also exhibits a wider range of results, including some outliers, suggesting variability depending on specific operational conditions or waste composition.

In conclusion, the choice between INC and LF must be contextualized within the specific environmental priorities and regulatory frameworks of the region in question. For instance, incineration may be preferable in areas with stringent emission controls and a need for energy recovery, while landfilling could be advantageous when methane capture is efficiently managed and resources for incineration infrastructure are limited. Each method presents distinct environmental impacts, underscoring the importance of a systems-based approach when evaluating waste management strategies.

3.11. Limitations and Prospects of LCA in MSWM

Life cycle assessment is an effective analytical method for comparing different waste management scenarios and technologies, finding wide practical application in waste management. Although there has been significant developments in regards to waste management, there are still a number of shortcomings in the approaches to LCA for MSWM [16]. The list of some limitations and solution are given in Table 2. First of all, the LCA method is focused on the assessment of the environmental impact itself. The economic factor is not sufficiently taken into account [78]. Therefore, further research is aimed at developing methods to assess the payback of environmental actions in terms of the relationship between the cost of the action and the resulting effect. Secondly, LCA is now being integrated across both temporal and spatial dimensions. [79]. Meanwhile, environmental impacts depend significantly on the location and specifically, on the region (country). In terms of time, LCA is more future-oriented than present-oriented. Next, the lack of databases remains a challenging issue because the strength of each analysis pivots on the accessibility of data for measurements [80]. Another important challenge is to effectively interpret the LCA results so that they can be used to make sound decisions [50]. This indicates that not only LCA, but also other tools for ecological systems should be the basis for decision making. Obviously, overcoming these contradictions is the main objective of the development of LCA.

Many studies have been performed to analyze the scope, limitations, and potential of LCA as a decision support method for waste management [28,50]. The methodology of and scientific approach to assessing impacts at the life cycle stages is still under development. The process mainly involves combining inventory analysis data with specific potential environmental impacts and an understanding of the role of such impacts. Currently, there is no universally accepted methodology to ensure consistency and accuracy in the correlation of inventory analysis data with potential environmental impacts. Therefore, one of the

most critical elements in impact assessment is transparency so that assumptions made are clearly described and documented.

Table 2. Limitations of and solutions for LCA studies.

	Current Challenges	Solutions and Improvements
1	Levels of waste formation, waste composition, and waste management methods may change over time, posing challenges for reflecting time changes in LCA models.	Design flexible LCA models that take into consideration the time-variability of waste formation and management policies, thereby providing more relevant and accurate environmental impact evaluations.
2	Conventional LCA models often focus on environmental impacts, neglecting social and economic aspects. They may also concentrate on a single waste management method, ignoring alternative approaches.	Enhance LCA models to include a broader range of impact categories to better capture the full spectrum of environmental impacts from waste management operations.
3	Obtaining accurate and comprehensive data for LCA surveys of household waste is challenging. Variations in waste generation, collection methods, and recycling practices across regions and households can lead to data gaps and inconsistencies.	Foster collaboration among scientists, waste management authorities, and policymakers to establish standardized data collection protocols and databases for household waste generation, composition, formation rates, and management methods.
4	Setting framework boundaries for the LCA of municipal waste is complex, as the choice of life cycle phases can significantly influence the environmental impact results.	Create clear and consistent guidelines for determining system boundaries in the household waste management life cycle, accounting for both direct and indirect environmental impacts.
5	Absence of some information in LCA studies; some of the articles we reviewed did not mention important information such as functional unit, LCA software, or LCIA method.	For the LCA study's results to be reliable and comparable, it is essential to mention every aspect of the research, not only for readers but also for future research.

4. Conclusions

This reviewed analyzed research articles from across the globe to provide an overview of LCA methodology, discussed the development of different software tools, highlighted the limitations and prospects of LCA, and finally evaluated the environmental impact of the most widespread MSWM options. Among the used LCA software, SimaPro, GaBi, EASETECH, EASEWASTE, and WISARD appeared more often than the others. We have analyzed the application, strengths, and disadvantages of each software. SimaPro and GaBi offer extensive databases (e.g., Ecoinvent) suitable for advanced LCAs, supporting various waste treatments (landfilling, incineration, recycling, composting). Their high cost and aggregated data may limit their use for specialized applications. EASEWASTE and EASETECH are tailored for detailed waste management analysis, especially for mixed flows, but lack broader environmental assessment flexibility. WISARD provides location-specific insights but offers limited, less frequently updated data. Choosing an LCA tool depends on balancing data scope, flexibility, and cost with MSWM needs.

The current LCA practices for municipal solid waste management (MSWM) face critical limitations, including time-sensitive waste dynamics, overlooked socio-economic factors, data inconsistencies, unclear boundaries, and incomplete reporting, which restrict their effectiveness. To improve LCA for MSWM, it is essential to develop adaptive frameworks that include standardization, flexible models capturing temporal variations, expanded environmental and socio-economic impact categories, increased transparency, standardized data collection, and clear system boundaries. Comprehensive documentation

will also improve reliability and comparability. These advancements will enable more informed and sustainable waste management decisions.

From a life cycle perspective, INC tends to have higher impacts on GWP, AP, and POCP, mainly due to emissions, but these can be partially mitigated by energy recovery and advanced emission controls. LF, on the other hand, shows significant impacts on GWP, EP, HTP, and NEP due to methane emissions, nutrient-rich leachate, and potential long-term soil and water contamination. Both methods display areas where advanced management practices can reduce these environmental impacts, making the choice between INC and LF highly context-dependent, based on available technology and regulatory standards.

This review underscores the essential aspects of LCA applications, along with their limitations and areas for improvement, evaluates the advantages and disadvantages of LCA software tools, and analyzes the environmental impacts of INC and LF. By offering general and fresh guidance on the LCA of MSW, our study will be useful for both specialists and policy makers. Future review studies should include other types of waste, along with the economic aspects of LCA.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17010302/s1. Table S1. LCA Studies on Municipal Waste Management.

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