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Review Article

Life Cycle Assessment (LCA) of Solid Waste Management Systems in African Countries: A Systematic Review

Etido Udoh Elijah[1*], Damilola Oluwatobi Ojo[2], Emmanuel Alura Yakubu[3], Ezinne Bertila Ezeuzo[4], Chima Cyril Hampo[5], Aminat Abubakar[6]

[1]Department of Geography and Environmental Management, Ahmadu Bello University, Zaria, Kaduna State, Nigeria
[2]Department of Forestry and Wildlife Management, Federal University of Agriculture, Abeokuta, Ogun State, Nigeria
[3]Department of Physical Sciences Education, Modibbo Adama University, Yola, Adamawa State, Nigeria
[4]Department of Social and Environmental Forestry, University of Ibadan, Ibadan, Oyo State, Nigeria
[5]Department of Civil, Architectural and Environmental Engineering, Drexel University, Drexel, Philadelphia, 19104, USA
[6]Department of Urban and Regional Planning, Federal Polytechnic Offa, Kwara State, Nigeria

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***Corresponding author:**
Etido Udoh Elijah,
Email: elijahetido@gmail.com

Abstract
Life cycle assessment (LCA) is a vital tool for evaluating the environmental burden of solid waste. This study investigated the outcomes of selected studies that applied the LCA methodology in assessing the environmental consequences of solid waste management (SWM) systems in Africa. Thirteen process-based LCA studies on SWM were reviewed, drawing from established criteria in databases such as SCOPUS, Elsevier, and Google Scholar. These studies were distributed across various African countries, with three conducted in Mauritius and Nigeria each, two in Zimbabwe and South Africa each, and one in Tanzania, Ghana, and Uganda, respectively. The evaluated parameters included aspects such as goal and scope, functional unit, system boundary, impact assessment categories, and sensitivity analysis. The findings revealed that majority of the studies employed similar waste management scenarios to determine the most environment-friendly, yet they differed considerably in some parameters. Climate change and global warming were the most assessed impact categories. Municipal solid waste (MSW) and plastic waste were the leading waste categories. MSW typically comprises paper, bottles, metal, plastics, glass, organics, and mixed waste proportions. The study also stated that the lack of reliable data on solid waste was a significant challenge faced by African countries in LCA studies. The paper's findings highlighted that a significant number of the studies, particularly in Nigeria, did not incorporate sensitivity analysis into their assessments, a crucial component for result interpretation. Consequently, the study emphasizes the importance of conducting more LCA research studies in African countries to produce pertinent data on SWM.
Keywords: Recycling, Composting, Incineration, Landfilling, Nigeria, Mauritius, Environmental impact

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Introduction

Current solid waste management (SWM) challenges affect numerous African countries as they grapple with rising waste production rates that strain existing waste management systems. The increase in urbanization and economic growth has led to a surge in solid waste generation.[1] According to Hoornweg and Bhada-Tata,[2] developing nations contribute a significant portion, approximately fifty-four percent, of the global waste output, which amounts to over 3.5 million tons per day or 1.3 billion tons annually. Research has demonstrated that the majority of this waste originates from developing countries, with urban regions being major contributors. As an example, Latin America accounted for approximately 369 000 tons of municipal solid waste (MSW), with urban centers contributing 56% of this total.[1] Similarly, in 2015, the United States managed to recycle and compost about 34% of the 260 million tons of solid waste it generated.[3] Waste management measures like recycling, landfilling, and incineration are applied to reduce the detrimental impacts of waste materials and help to safeguard humans and the environment. Conversely, due to limited urban infrastructure, a significant part of the waste collected in urban areas is not properly managed in Africa.[1] Nevertheless, some people in Africa survive by collecting waste materials at disposal sites for a living.[4] It was estimated that Nigeria, with the largest population in Africa, collected about 30% of the 32 million tons of solid waste produced yearly, being a top producer of solid waste.[5] The major issues of SWM in developing countries encompass lack of technical capacity, lack of research studies, and improper planning for waste management systems.[1] The waste collection from African homes is poorly implemented despite the waste management systems. In Ghana, waste collection usually leads to overflowing illegal landfills. Likewise, in Nigeria, the waste is indiscriminately dumped along drainage channels and ditches, roads, and open environments.[6] To address the waste management challenges, the African Union has set an ambitious goal: by 2023, African cities aim to increase their waste recycling rates from a mere ten percent to a minimum of fifty percent. This objective relies on concerted efforts and collaboration among key stakeholders.[6] On the other hand, it was estimated that by 2025, Africa will produce around 250 million tons of waste, and most of which is disposed of at landfills and uncontrolled dumpsites.[6] Consequently, African cities must select and implement environmental-friendly waste management options to curtail the effects of waste through life cycle assessment (LCA). To this end, past LCA studies on SWM were reviewed to discuss and elaborate the obtained findings, discover gaps and proffer suggestions for future LCA studies on SWM in Africa. This review also assessed the similarities and differences between the studies, and their limitations.

Categories of Solid Waste

The material produced by human activities and discarded as useless and unwanted can be considered solid waste.[7] It was classified into municipal, industrial, electronic, agricultural, and biomedical waste based on the sources.[8,9] MSWs are primarily produced from residential, industrial and commercial sources.[10] It comprises plastics, metals, organic waste (food and garden), glass, and paper or cardboard.[11] The categories of solid waste assessed in this study were plastic, construction and demolition, animal, e-waste and MSW, as summarised in Table 1. Plastic waste has been a principal part of MSW. Plastic waste, like solid waste, may be grouped into municipal, medical and industrial waste. The most common plastic resin types of plastic waste are polyethene terephthalate (PET), polyethylene (PE), polyvinyl alcohol, and polypropylene.[12] Agricultural waste comprises plant remnants, silage discharge, and animal droppings.[13] Urban animal farming is becoming increasingly significant in feeding many Sub-Saharan African cities' growing populations. Due to space constraints, managing the generated animal manure is proving difficult.[14]

Additionally, massive amounts of construction and demolition waste (CDW) are generated during the construction and demolition of buildings and civil engineering works.[27] According to Menegaki and

Table 1. Selected Studies in Africa and Their Parameters

Year/Publication	Types of Waste	Functional Unit	LCIA Method/ Software	Impact Categories
2007, Mbohwa and Manjera[15]	Plastic	1 kg	Gabi 3.0	Resource depletion, GWP, ozone depletion (OD), Photochemical oxidant formation (POF), Acidification Potential (AP), Eutrophication Potential (EP), Human Toxicity (HT), Ecotoxicity
2008, Foolmaun and Ramjeeawon[16]	Plastic (PET)	1 tonne	Eco-indicator 99 End-point, SimaPro 5.1	Terrestrial ecotoxicity (TE), Human toxicity (HT), POF, GWP, AP
2011, Foolmaun and Ramjeeawon [17]	Plastic (Used PET bottles)	1 tonne	Eco-indicator 99, SimaPro 7.1	Carcinogens, Respiratory organics/inorganics, Climate change (CC), Ecotoxicity, OD, AP, EP
2014, Ojoawo et al[18]	MSW - Paper, Glass, Textiles, organics	1 kg	CML and TRACI, GaBi5 Modelling tool	GWP, AP, EP, and ODP
2014, Vossberg et al[19]	Construction and demolition, container glass	1 tonne	SimaPro 7	Cumulative energy demand and GWP
2015, Ogundipe and Jimoh[20]	MSW	1 tonne	Impact 2002+, SimaPro 7.2	Carcinogen, Ecotoxicity, AP, Eutrophication, GWP
2016, Komakech et al[14]	Animal manure	1 tonne	CML 2002	GWP, EP
2017, Rajcoomar and Ramjeawon[21]	MSW	427,687 tonnes	CML-IA, ReCiPe end-point, SimaPro 8.0.4.30	Abiotic depletion potential, GWP, OD, HT, TE, POF, AP and EP
2019, Balogun-Adeleye et al[22]	MSW	1 tonne	Landfill Gas Emission v3.02	GWP
2019, Nhubu and Muzenda[23]	MSW	467,303 tonnes	ReCiPe endpoint, SimaPro	GWP, AP, Eutrophication, and HT
2020, Yong[24]	e-waste	1000 kg	ReCiPe method, CMLCA 6.1	TE, CC, Fossil depletion (FD), HT, Particulate matter formation (PMF)
2020, Chitaka et al[25]	Plastic, paper, steel, and glass (straw types)	36 disposable straws & 1 reusable straws	ReCiPe MidPoint (H), SimaPro	CC, OD, HT, POF, Terrestrial/Freshwater acidification & ecotoxicity, Eutrophication, Ecotoxicity, PMF, Ionizing radiation, Natural land transformation, Fossil/Water/Metal depletion
2021, Richard et al[26]	MSW	1 tonne	ReCiPe 2008 Midpoint (H) 1.133, Umberto, ecoinvent 3v6 database	CC, POF, FEE, Terrestrial acidification & Ecotoxicity, HT, and PMF

Damigos,[28] 35% of CDW, which is estimated at over 100 million tons, contribute to landfill disposal globally, without any treatment. E-waste, which refers to discarded electronic devices, can be safely recycled. The rising production of electronic products has increased electronic waste (e-waste) issues, which is already considered the world's fastest-growing waste stream, with an estimated growth rate of 3 to 5% annually.[29] Nonetheless, only 20% of the global e-waste is recycled, with the remainder being stored, reused, exported, disposed of in landfills, or incinerated.[30]

Overview of Waste Management in Africa

Waste management is a significant environmental problem in Africa, heavily influenced by industrialization and urbanization. One major challenge facing waste management in Africa is the local government institutions' failure to manage urbanization adequately.[31] For example, in East African cities, the need for waste collection expanded in tandem with the population growth, followed by the rise of communities inhabited mostly by low-income workers with barely any waste management activities. Thus, waste services were poor, leading to waste heaps that posed environmental health risks.[32]

Waste management is critical to the sustainable development of Africa, and it presents investment opportunities in carbon credits aimed at reducing greenhouse gases (GHG) emissions. According to Couth and Trois,[33] municipal wastes in Africa are disposed of indiscriminately, resulting in GHG emissions. Hence, the Africa governments must decentralize waste management to reduce GHG emissions through public-private partnerships. On the contrary, in some Nigerian cities, state government agencies (sub-national governments) monopolized waste management with little capacity to solve SWM concerns including inadequate waste collection, poor disposal methods, and inadequate financing.[34]

Recycling in South Africa has existed for more than three decades, spurred by social and economic needs. The most common products recycled include glass, Aluminum, tinplate, plastics, paper, and cardboard.[32] Although South Africa successfully grew a recycling economy from the efforts of the informal waste sector over the past three decades, significant quantities of waste such as recyclables are still disposed of in landfills. Furthermore, its extensive regulatory framework rendered public and private sector compliance more challenging and competitive on a local and global scale, thereby driving waste away from landfills towards reuse, recycling, and recovery.[31] Moreover, informal garbage pickers were critical in gaining access to resources that the private sector failed to obtain owing to municipal gatekeeping.[33] Notwithstanding, waste remains a severe environmental concern common to all African urban areas. Waste management suffered many setbacks in African cities, such as inadequate financing, inadequate collection, and disposal systems, and a lack of database management systems.[35]

Waste Management Hierarchy

Waste management hierarchy is an approach that prioritizes waste reduction, recycling, and reuse over waste treatment and disposal.[36] It depicts the progression of a material or product through several waste management phases and reflects the final stage of a product's life cycle as illustrated using a pyramid in Figure 1.[37] Also, it intends to derive the most practical value from products while generating the least garbage.

The most preferred option in the waste hierarchy approach (WHA) is waste prevention, and it requires a reduction of waste and the extension of a product's lifespan, thus delaying its entry into the waste category.[38] Waste prevention involves reducing the number of hazardous compounds in the trash and replacing renewable resources with non-renewable ones in manufacturing operations.

Waste reuse refers to any action in which items or components not trashed are channeled for their original purpose.[39] Such actions include fixing, cleaning, refurbishing, and reconditioning. Waste reuse includes refilled bottles, recycled boxes, plastic seedling pots, and refillable pens. The increased emphasis on waste reuse has resulted in a gradual shift toward viewing waste as a resource (resource-based paradigm) rather than a problem to be avoided (refuse-based paradigm).[40]

Recycling is any procedure in which waste materials are transformed for original or other uses into by-products or materials to achieve priority end-of-waste status with waste material. Reprocessing procedures can generate new products with a greater (up-cycling) or lower (down-cycling) function than waste sources.[38] The high collection, transportation, and reprocessing costs lowered recycling activities in the hierarchy.

Waste recovery activities include preparing and using waste to serve a crucial role by replacing other resources used for similar purposes,[39] thereby reducing the need for landfill sites and deriving maximum value.[41] The least important aspect is disposal, which entails the treatment and disposal of wastes that cannot be reused, recycled, or recovered, primarily through safe landfilling, burning, and discharge into bodies of water.[42] After exploring all diversion, reuse, and valorisation, it is the option employed for the waste residues.[37] Solid waste disposal methods include open dumping, landfilling, composting, and incineration.

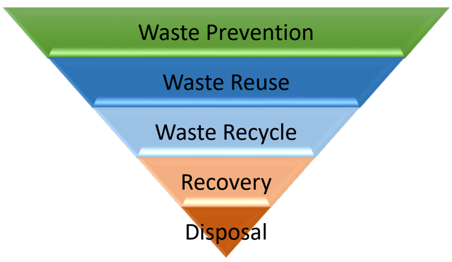

Figure 1. The Waste Management Hierarchy

However, studies in Africa have demonstrated that the continent is still far from fully embracing the WHA, despite prioritizing waste recycling as a critical action under Africa Vision 2030.[43]

Life Cycle Assessment

Manufacturers first embraced LCA in the early 1970s as a means to enhance their product efficiency. In the 21st century, LCA has found application in improving waste management processes. Essentially, LCA involves the quantification and consideration of a product's environmental impact throughout its entire lifecycle. It employs a cradle-to-grave approach, commencing with raw material extraction and concluding with product recycling or disposal. The International Standards Organization[44] has established the standards governing LCA procedures.[45] LCA provides valuable insights to policymakers regarding a product's environmental impacts and facilitates comparisons of alternative strategies in terms of highlighted environmental impact categories, such as the reduction of greenhouse gas emissions.

The main phases of LCA are as follows:

1. *Goal and scope:* It explains the purpose of the study and the product's function.
2. *Inventory analysis:* It entails the collection, validation, and aggregation of input and output data to measure internal processes linked with each life cycle stage, such as energy utilization, waste creation, and material use.
3. *Impact assessment:* During this stage, characterization models, impact categories, weighting values, category indicators, and equivalence variables are scrutinized. This analysis serves to translate the collected data into potential implications for public health and the environment.
4. *Results interpretation:* This phase is determined by the preceding stages. The interpretation of the result identifies significant potential impacts and proffers methods for reducing environmental burdens, material use, or alternative material or process.

Materials and Methods

Criteria for Selection

This review captured the significant LCA studies on solid waste in Africa that met the selection criteria, considering the release year of the final international standard[44] for LCA between 2006 and 2021 (Figure 2). Thirteen process-based LCA of SWM systems reported in English were collected and assessed following the selection criteria adopted by various researchers.[46,47] The subject matters addressed in each article were identified through content analysis. However, Africa has a low number of LCA studies, which could be due to the region's low adoption of the LCA methodology.

A database search was conducted on SCOPUS, Science Direct/Elsevier, Google Scholar, and online google search engine using the following keywords: "Life Cycle Assessment", "Solid Waste Management", and "Africa",

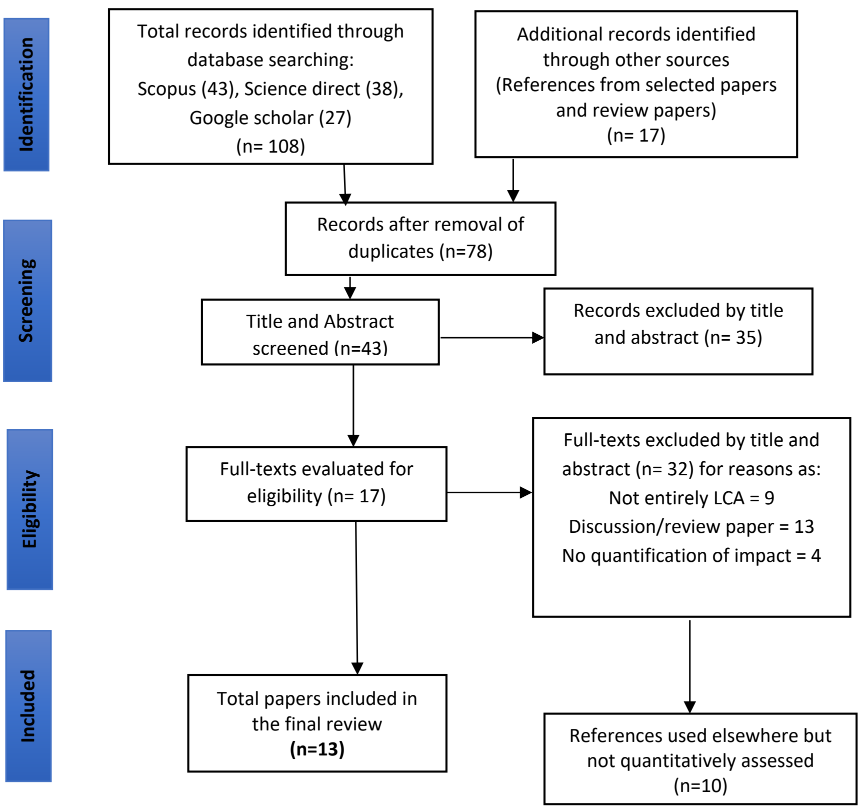

Figure 2. Screening Process for Selected Studies in Africa

including each African country's name (e.g., "Nigeria", "Tanzania", "Ghana, "Morocco"). Due to insufficient LCA studies in Africa, the search criteria were modified to classify the different types of solid waste in each African country as follows: "Plastics", "Wood", "Glass", "Metals", "Paper/Cardboard", "Organic waste" and "E-waste". Additionally, the keyword "Environmental Impact" was used to get relevant results since some environmental impact studies were conducted using the LCA methodology. The excluded papers were also checked to reveal any relevant references for consideration. The review process for selecting the relevant articles spanned an estimated timeframe of six months from June 2021 to December 2021.

The relevant papers were those that fulfilled the following conditions (Figure 2):

1. Original research studies in African countries that assessed the environmental implications of solid waste and alternative SWM systems.
2. Environmental impact studies that applied the LCA methodology and quantified the results from the impact assessment accordingly.
3. Studies with a distinct methodology, goal and scope, functional unit, impact assessment, and system boundary.

Results

Assessment of Selected Parameters

The selected parameters of the shortlisted studies were assessed according to the requirements and international standards of LCA.[44] Each study was assessed critically considering the approach used in the following sections:

Goal and Scope of LCA

The goal and scope are crucial components of LCA that define the study's aim and extent. It is expected that every LCA study will define the goal and scope as laid out by the LCA principles. It also describes the assumptions, system boundaries, and functional unit. The goals and scopes of the various research studies vary based on the life cycle techniques, the types of solid waste analyzed, and the disposal solutions investigated.

This review was tailored to studies that assessed the environmental impact of solid waste using the LCA Methodology. More than sixty per cent of the studies shared a similar goal of assessing and comparing the environmental impacts of alternative SWM scenarios (Figure 3). Foolmaun and Ramjeeawon[16,17] conducted two studies in Mauritius to assess the environmental effects, i.e., the post-consumer effect following collection of three and five SWM options for used plastic (PET) bottles, respectively. Likewise, Nhubu and Muzenda[23] assessed the environmental effects of six suggested SWM systems for implementation in Zimbabwe, Harare, and its dormitory towns. The Municipal Solid Waste Management (MSWM) scenarios involved a combination of disposal without treatment, incineration (with and without energy

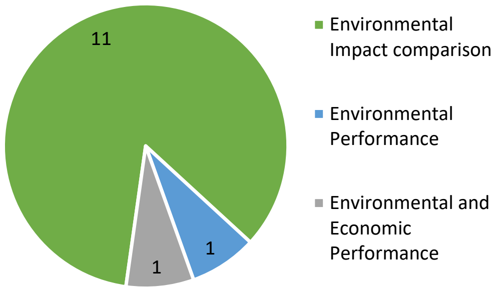

Figure 3. Goal/Scope of Reviewed Studies

recovery), anaerobic digestion, reuse and recycling, and landfilling. Similarly, Richard et al[36] assessed the environmental effects of several SWM options, which were different combinations of recycling, composting, landfilling, and anaerobic digestion. Also, Ogundipe and Jimoh[20] conducted a study in Minna, Niger State, Nigeria, to assess the environmental effects of three waste management options and select an environment-friendly waste management system as an alternative to the existing waste management system. The reviewed studies revealed significant similarities due to the overarching nature of their goals and scopes, which assessed similar waste management scenarios to select the most environment-friendly system.

Functional Unit

A functional unit is a quantifiable description of the purpose of a product which serves as a basis for all impact assessment calculations.[48] The component of a functional unit in a review study accounts for a number of assessed LCAs that offer a clear description of the primary (i.e., non-compensatory) functional unit.[49] For the SWM system investigated using LCA, this clear definition mandates the usage of the term 'functional unit,' as well as its description.

The functional units adopted in the reviewed LCA studies were tonne, metric ton, and kilogram, as shown in Table 1. It was discovered that one ton of waste is the most widely used Functional Unit among the reviewed studies. It was used as a functional unit in six studies.[14,16,17,19,20] Two studies used one metric ton of waste,[22,26] and some studies used one kg of waste.[15,18] Yong used 1000 kg of collected end-of-life phones,[24] excluding batteries. Similarly, Rajcoomar and Ramjeawon[21] chose 427 687 tons of MSW, whereas Nhubu and Muzenda[23] used 467 303 tons of MSW generated annually as the functional unit. Conversely, Finally, Chitaka et al[25] used 36 disposable straws and one reusable straw as functional unit.

In most waste management systems, the functional unit is chosen based on materials, energy, geographic location, distance, specific mass, volume, and emissions (air, water, and land). Nevertheless, the choice of functional unit is usually determined by the study's goal and scope.[50]

Impact Assessment Categories

The Life Cycle Impact Assessment (LCIA) was executed to assess the environmental implications of SWM within the context of the study's aim and scope. This process could involve inventory analysis to understand the specific environmental impacts. The measurement of impact data is quantified by dividing emissions into different categories of comparable units. The choice and definition of an impact category heavily depend on the methodology used for the research's LSA and objectives.[47] However, due to different methodologies and objectives, the outcome of an impact assessment category may be different across other research due to determining factors such as functional unit or system boundaries.

In similar manner to the goal and scope, over seventy per cent of the studies[14-16,18-23] assessed the global warming potential (GWP), which was also used interchangeably with climate change potential[17,25,26] in some studies. While the majority of the studies evaluated a minimum of five impact categories, there was one exception[22] that focused solely on a single impact category. Impact categories must be assessed in LCA studies because it helps to quantify the environmental effects of the product or system. The impact categories considered according to the choice of the LCIA technique and software applied have been summarized in Table 1.

System Boundaries

The fundamental objective of system boundary assessment is to depict the processes or activities in the LCA, including the system's inputs, outputs and study's purpose. Thus, the selection of the system boundary is strongly tied to the goal description. It is vital to determine the extent of the research limits of solid wastes using LCA and the extent of waste generation management. According to Komakech et al,[14] the system boundary is often defined from collecting waste materials after use to disposal by landfill, incineration, or recycling. The phases that were assessed within this review in the system boundary were mostly sorted to end-of-life (disposal). The use stage was omitted in the system boundaries due to its minimal environmental effect. The typical cradle-to-grave approach for solid waste begins from waste collection through to the disposal stage, considering the diverse disposal options and the environmental impact. The similarities in the goal and scope of the reviewed studies are also reflected in the system boundaries used. As summarized in Table 2, most reviewed studies implemented a cradle to grave LCA approach. However, four studies considered more than one approach.[14,15,19,24] In contrast, Vossberg et al[19] implemented the cradle-to-cradle LCA in their study. However, the study was limited in scope, focusing only on estimating the greenhouse gas implications for the recycled materials compared to the other studies reviewed.

Sensitivity analysis

Sensitivity analysis plays a vital role in the LCA interpretation step. It shows the influence of each input parameter on the LCA outcome (measurement of

Table 2. System boundaries of the reviewed studies in Africa

Year/Publication	Start Process	Intermediate Processes	End Processes (Scenario) Investigated	System Boundaries
2007, Mbohwa & Manjera[15]	Manufacturing, waste collection	Transportation, recycling, shredding, washing and drying	Recycled plastics, landfilling	Cradle to gate, cradle to grave
2008, Foolmaun & Ramjeawon[16]	Raw materials extraction, Manufacture, and importation	PET pellets conversion, distribution	Landfilling, incineration	Cradle to grave
2011, Foolmaun and Ramjeeawo[17]	Post-consumer collection.	Transportation, recycling	Landfilling, incineration (energy recovery), flake production	Cradle to grave
2014, Ojoawo et al[18]	Post-consumer collection of demolished container glasses.	Transportation	Landfilling, virgin aggregate production, offsite and onsite recycling	Cradle to grave, cradle to cradle
2014, Vossberg et al[19]	Waste collection	Transportation	Landfilling	Cradle to grave
2015, Ogundipe & Jimoh[20]	Waste collection	Sorting of recyclables, transportation	Recycled products, compost, landfilling, and incineration	Cradle to grave
2016, Komakech et al[14]	Waste generation and collection	Pre-treatment composting and vermicomposting process	Vermicompost	Cradle to gate, cradle to grave
2016, Rajcoomar & Ramjeawon[21]	Waste generation and collection	Transportation	Landfill (energy recovery), incineration (energy recovery), Compost/recycled products	Cradle to grave
2019, Nhubu & Muzenda[23]	Waste collection	Transportation, Landfilling	Landfill	Cradle to grave
2019, Balogun-Adeleye et al[22]	Waste generation and collection	Waste treatment, incineration, landfilling, anaerobic digestion	Landfill (energy recovery), incineration (energy recovery, material recovery, and aerobic treatment)	Cradle to grave
2020, Chitaka et al[25]	Raw material extraction and straw manufacture	Distribution, retail, and usage	Marine environment disposal, Open burning, Landfill, Recycled straw	Cradle to grave
2020, Yong[24]	Waste collection	Mechanical dismantling (informal), transportation, leaching, smelting, extraction, and residue treatment	Landfill, Fire refining, and anode casting for copper anode production	Cradle to cradle, Cradle to grave
2021, Richard et al[26]	Waste collection	Transportation, sorting, recycling, sanitary landfilling, composting, and anaerobic digestion	Recycling and sanitary landfill, composting, anaerobic digestion	Cradle to grave

impact categories). A sensitive parameter is one whose modification significantly impacts the outcome. It is accomplished by variational analysis that modifies each input parameter within a 10% limit of its actual value without affecting the remaining input parameters.[47] Sensitivity analysis can be conducted by changing a subset of the input parameters one at a time to determine how much effect it has on the findings. Although this method has numerous advantages, large systems are cumbersome and may not ignore some characteristics or possibly crucial parameters. The outcome is applied to analyze the sensitivity proportions and coefficients of the altered input parameter.

Some studies overlooked sensitivity analysis, while some did not give enough information about it in their LCA research. Nonetheless, it is a significant part of LCA. Approximately fifty per cent of the research studies[14,16,19,21,23,25,26] conducted sensitivity analysis to examine the effect of modifying various factors on the outcome of the study. However, none of the studies in Nigeria carried out sensitivity analysis. It could be due to the priority accorded to the sensitivity analysis by the researcher or the method employed by the studies in Nigeria.

One study[23] showed that increasing materials recovery levels by about 28% for waste management scenarios will result in zero acidification potentials for the alternative waste management system. In the same vein, Komakech et al[14] did a sensitivity analysis to demonstrate that the application of animal manure directly to the crop fields had a tremendous positive impact on the GWP compared to the current baseline system in Uganda. Similarly, Chitaka et al[25] assessed the effects of variables such as washing water volume, temperature, and means of transportation on glass straw emissions. The results indicated that variations in the parameters affected the contribution in the impact categories, from negligible to very significant. Richard et al[26] concluded that improvement in the processes which contributed to the impact would result in a positive impact. He assessed the sensitivity to process improvement and the LCIA methods.[26] It revealed that reducing methane emissions benefitted all the alternative waste management scenarios, and improvements in diesel consumption and electrification consumption had significant effects on the impact categories. Therefore, the necessity for sensitivity analysis when conducting LCA studies should not be underestimated.

Study Location

The location where the study was carried out can determine the research results. According to Alhazmi et al,[47] developing countries, especially Africa, are significantly impacted by unavailability of data, as evidenced by the dearth of studies on LCA of SWM in African countries. He attributed this challenge to the fact that many African countries have yet to implement measures to curtail the environmental impact of solid waste, despite understanding its significant impact on the economy. The study also noted that although many African countries have developed an awareness of the dire need for LCA in the last decade, much work is still required. All the studies were conducted in Africa (Figure 4); three studies were carried out in Mauritius and Nigeria, respectively; two studies originated from Zimbabwe and South Africa respectively; one study each from Tanzania, Ghana, and Uganda, respectively.

A significant reason for the shortage of LCA studies in Africa, as evident in Figure 1, is the lack and uncertainty of the data.[47] Some of these studies[15,16,23-25] highlighted the unavailability of data as one of the limitations of their studies while recommending for more LCA studies to be carried out on waste management. Mbohwa and Manjera[15] identified some limitations to data availability as inconsistencies in technology used and data confidentiality. Komakech et al[14] noted that their study was designed for Kampala as a case study, but due to unavailable data for Kampala, data from other cities were implemented.

Discussion

This study revealed that the earliest LCA study on solid waste in Africa was undertaken in 2007[15] after the international standard for LCA was released in 2006 (ISO 14040, 2006) (Figure 5). Many African countries are yet to publish papers on LCA studies generally, especially on SWM; 46 of them have not published any paper on LCA of solid waste, and at least 25 African countries are yet to

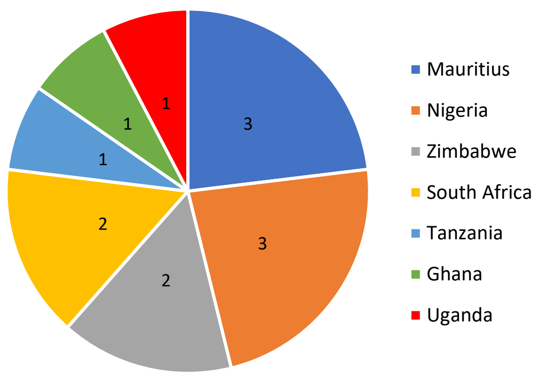

Figure 4. Distribution of the LCA Studies on SWM in Africa

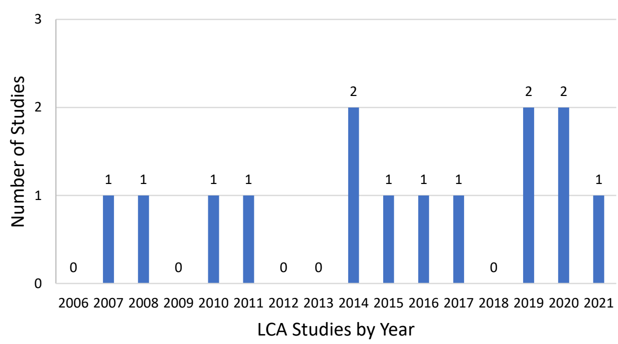

Figure 5. LCA Research Studies by Year of Publications

publish a single article on LCA research. Notwithstanding, at least seven LCA studies on SWM systems were published in Africa five years ago.[21-26] Sadly, the number of LCA studies in Africa pales significantly compared to developed countries like South Korea which have over 91 LCA studies with at least 12 on solid waste.[51]

Recycling is usually a key component of SWM options and it contributes to the reduction of environmental impact. However, Foolmaun and Ramjeeawon[37] noted that recycling was not considered in the study because recycling was not economically viable according to previous studies in the Mauritius waste sector. In contrast, Richard et al[26] found that combining recycling with composting and landfilling in Tanzania was economically feasible and environment-friendly. Several other studies in Africa[19,23,24] found recycling as a better alternative to landfilling and incineration. Likewise, in developed countries like Spain, the study by Mercante et al[52] showed that recycling contributed to savings for all the impact categories. In addition, transportation, sorting, and landfilling contributed more to the environmental impact as a result of the energy demand required.

The implementation of software and LCIA methodologies constitutes the backbone of LCA studies. Some studies[16,17,19-21,23,25] used Simapro software, though different versions, while Richard et al[26] used the Umberto Software LCA + as the LCA software. Simapro is the most widely used LCA software by academia, and it has been in development for 25 years. LCA software typically possesses both strengths and weaknesses. Therefore, there is a need to develop alternative software solutions to enhance performance. The studies conducted in developed countries, as listed in references,[52-57] predominantly utilized similar software. However, Rigamonti et al[58] opted for the EASE-WASTE software, complemented by the EDIP database developed by researchers in Denmark (see Table 3). Several studies conducted in Africa, as referenced,[23-26] utilized either the ReCiPe end-point or Midpoint methods. The choice of methodology significantly influenced the number and nature of impact categories assessed. Midpoint methods are specialized for addressing specific environmental concerns like global warming or climate change, whereas end-point approaches take a broader perspective, considering factors such as their impact on human health or biodiversity.

Global warming/climate change was the most assessed impact category in this review, followed by acidification and eutrophication. The findings of these studies are similar to LCA studies in developed countries[52-57] which also had global warming/climate change as the most assessed impact categories. SWM contributes significantly to climate change due to the energy demand required, especially for the incineration of solid wastes, which results in the emissions of GHGs. Foolmaun and Ramjeeawon[17] demonstrated that the combination of anaerobic digestion along with reuse, recycling, and incineration options resulted in the least environmental impact within the categories of Acidification, Eutrophication, Global Warming, and Human Health. In like manner, Rajcoomar and Ramjeawon[21] showed that incineration with recovered energy combined with recycling, composting, and landfilling had the most negligible human toxicity and ecotoxicity effect due to minimal production of NO_x and SO_2, which also contribute to climate change.

The reviewed studies strongly emphasized MSW, particularly for paper, bottles, metal, plastics, glass, organics, and mixed waste proportions, as shown in Table 1 and Figure 6. MSW typically represented the most significant waste category researched for LCA studies in African countries (Figure 6). Although some studies[19,22,26] assessed all the waste types to determine which had the most and least impact on the environment, other studies focused on either one type of waste or generally on MSW as summarized in Table 1.

Despite significant variations and similarities in the studies across African countries, this study only accounted for a relatively small portion of all waste types. Data scarcity was a significant stumbling block in conducting and publishing LCA studies on SWM. Laurent et al[59] rightly stated that lack of data can substantially hinder LCA studies and be the reason for analyzing specific waste categories. Also, public perception of environmental

Table 3. Selected LCA Studies on Solid Waste Management in Developed Countries and Their Parameters

Year/Publication	Country/ Continent	Type of Waste	Functional Unit	LCIA Method/Software	Impact Category	System Boundaries
2009, Banar et al[53]	Turkey	MSW	1 tonne	Simapro 7 (DQI)	CC, HT, AP, EP, POP	Cradle to grave
2010, Hong, Li and Zhaojie[54]	China	MSW	1 tonne dry MSW	IMPACT 2002 +	CC, OD, HT, POF, AP, EP, ETP, Resources depletion	Cradle to grave
2011, Mercante et al[52]	Spain	Construction and demolition waste	1 tonne of C&D waste	SimaPro 7, ecoinvent	POP, ODP, GWP, EP, AP	Cradle to grave
2014, Rigamonti et al[58]	Italy/France	Plastic waste	I tonne	EASE-WASTE, EDIP	GWP, AP, POF, ozone depletion	Cradle to grave
2015, Parkes at al.[55]	London, United Kingdom	MSW	15,847, 37,679 and 54,939 tonnes respectively, per scenario	GaBi model, CML	GWP, AP, EP, ADP	Cradle to grave
2015, Wäger and Hischier[56]	Central Europe	Plastics from E-waste	1 tonne plastic- rich WEEE	Ecoinvent v2.2, ReCiPe method	GWP, AP, EP, ETP, POF, HT,	Cradle to grave
2019, Khandelwal et al[57]	India	MSW	1 metric ton ne MSW	GaBi 8.5.0.79 model, CML-1A	GWP, AP, EP, ADO, HTP, POP	Cradle to grave

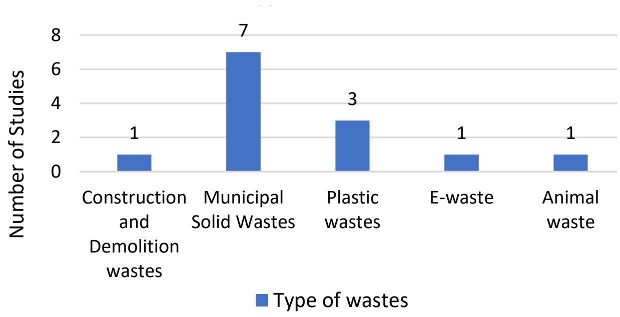

Figure 6. The Popular Type of Wastes Assessed by the Reviewed LCA Studies

issues plays a significant role in the LCA studies, mainly whether waste management is included in the public discourse, especially MSW.

The analysis of the LCA studies was important to understand the findings and conclusions drawn by certain studies and why some scenarios were favourable in one study and not the other. Although some studies shared similarities in LCA phases, different LCIA methodologies or software may have caused variations in the values of the measured impact categories, thereby producing entirely different and incomparable results. Differences in location, functional unit and goal also had a substantial influence on the variations. For instance, Foolmaun and Ramjeeawon[16,17] revealed that incineration with energy recovery was the least impactful waste management system in Mauritius, while in Tanzania,[39] a combination recycling with composting and landfilling scenarios had the least environmental impact. However, the impact assessment results were mostly quantitatively incomparable as these studies varied in their units of measurement or the impact categories considered.

The authors suggest that the implementation of a collective waste management options is highly effective and provides the greatest gains in effectively managing solid waste. In most cases, recycling provided the highest savings in energy production and consumption, however, it cannot be applied to all categories of waste. Furthermore, Incineration and landfilling generate heat and power and contribute significantly to GHG emissions. Although there was a strong similarity in the implementation of the LCA studies in developed countries and Africa, there is less LCA studies in Africa mostly due to unavailable data and finance. In the future, LCA researchers in Africa should study specific types of waste like metals, organic waste, and e-waste, other than MSW. It will shed light on similarities and variances, especially in their impact assessment categories.

Conclusion

This study revealed that the results of the literature reviewed were primarily influenced by the study's aim, scope, system boundaries, functional unit, geographical context, and waste management scenarios. Thirteen LCA studies were assessed for their similarities and differences in their approaches. Data scarcity accounted for insufficient LCA studies on SWM in Africa, especially in North and Central African countries. Based on the available literature, the dearth of LCA research studies on solid waste in Africa calls for more research. Most of the papers analysed similar waste management scenarios such as recycling, incineration, and landfilling in varying combinations to determine the most environment-friendly. Also, global warming and/or climate change was the most assessed impact category, which substantiates the contribution of solid waste to the negative impacts of climate change in the world today. To achieve sustainable waste management, the waste management hierarchy should be combined with LCA studies. In the future, it is also crucial that LCA studies include sensitivity analysis, which was lacking in the interpretation of results. Government should enact policies to drive more LCA studies in SWM.

Thus, LCA methods should be considered for the productive and effective management of resources. To conclude, LCA can be applied as a critical tool for achieving long-term benefits, particularly in strategically designing a sustainable SWM system in Africa. LCA studies should be the norm in Africa when assessing waste management options to achieve sustainability. LCA studies should be reviewed and reiterated after some time, especially when there is an advancement in waste management technologies to ensure that the current waste management option is the most environmentally friendly.

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Authors' Contribution

Conceptualization: Chima Cyril Hampo.
Data curation: Etido Udoh Elijah.
Formal analysis: Etido Udoh Elijah.
Funding acquisition: There was no funding for this work.
Investigation: Etido Udoh Elijah.
Methodology: Etido Udoh Elijah.
Project Administration: Etido Udoh Elijah, Chima Cyril Hampo.
Resources: Etido Udoh Elijah, Damilola Oluwatobi Ojo.
Supervision: Etido Udoh Elijah.
Validation: Etido Udoh Elijah.
Visualization: Etido Udoh Elijah.
Writing–original draft: Etido Udoh Elijah, Emmanuel Alura Yakubu, Damilola Oluwatobi Ojo, Ezinne Bertila Ezeuzo, Aminat Abubakar.
Writing–review & editing: Etido Udoh Elijah, Damilola Oluwatobi Ojo.

Competing Interests

The authors declare they have no competing interests.

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