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Life Cycle Sustainability Assessment of Electricity Generation from Municipal Solid Waste in Nigeria: A Prospective Study

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Abstract: Globally, rising population and rapid urbanisation have resulted in the dual issues of increased electricity demand and waste generation. These exacerbate diverse global problems, ranging from irregular electricity supply and inadequate waste management systems to water/air/soil pollution, climate change, etc. Waste-to-Energy (WtE) approaches have been proposed and developed to address simultaneously these two issues through energy recovery from waste. However, the variety of available waste materials and different WtE technologies make the choice of an appropriate technology challenging for decision-makers. The evaluation of the different WtE technologies in terms of their sustainability could provide a solid comparative base for strategic decision making in the power and waste management domains. This paper presents research conducted using a multidimensional Life Cycle Sustainability Assessment (LCSA) approach to estimate and compare the environmental, economic, and social impacts associated with the generation of electricity from Municipal Solid Waste (MSW) in two major cities, Lagos and Abuja, in Nigeria. These cities provide case studies in a developing world context to explore how their similarities and differences may influence the LCSA impacts for four WtE systems (Anaerobic Digestion, Incineration, Gasification, and Landfill Gas to Energy), and this is the first research of its kind. An LCSA ranking and scoring system and a muti-attribute value theory (MAVT) multi-criteria decision analysis (MCDA) were employed to evaluate the overall sustainability of the prospective use of WtE over a 20-year timeframe. The results from both approaches indicated that the adoption of WtE offered sustainability benefits for both cities, marginally more so for Lagos than Abuja. It was concluded that, for optimal benefits to be achieved, it is vital for decision-makers to think about the various trade-offs revealed by this type of analysis and the varying priorities of relevant stakeholders.

Keywords: municipal solid waste; waste management; electricity supply; waste to energy; life cycle assessment; life cycle costing; social life cycle assessment; life cycle sustainability assessment; multi-criteria decision analysis

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1. Introduction

The societal development depends greatly on an adequate energy supply [1]. According to [2], total global energy consumption has increased significantly from 8560 to 13,730 million tonnes of oil equivalent from 1990 to 2017. The fossil fuel-controlled energy system has led to greenhouse gas (GHG) emissions, which has resulted in climate change [1]. Apart from this, the rising global population, as well as fast urbanisation, particularly in developing countries, has also led to problems such as energy shortages as well as inadequate waste management. In recent years, waste has been produced at an increasing rate due to societal development. It is reported by the United Nations (UN) that the generation of worldwide municipal solid waste (MSW) rose from 1.3 billion tonnes in 2012 to 2.0 billion tonnes in 2016 and is projected to reach 3.4 billion tonnes by 2050 [3,4]. This has made waste management a major issue, especially in developing countries.

As part of addressing the dual issues of waste management and energy supply, different technologies such as incineration, anaerobic digestion (AD), gasification, and landfill gas to energy (LFGTE) have been proposed and developed as part of the concept of waste-to-energy (WtE) to recover energy from waste. This could prove beneficial for a developing country such as Nigeria, West Africa, with a population of over 200 million and over 42 million tonnes of solid waste produced annually [5], making the country one of the major producers of MSW in Sub-Sahara Africa [6]. In addition to this, the country is also faced with insufficient electricity generation and a poor transmission network, with the average demand for electricity being above 25,000 MW against a total installed electricity capacity that is barely above 12,000 MW [7]. However, the various WtE technologies available, along with different waste materials, have made the selection of suitable technology or combination of technologies challenging for decision-makers [1]. Therefore, the assessment of WtE technologies from a sustainability perspective could offer a comparative base assisting such choices [1]. Life Cycle Sustainability Assessment (LCSA) is an evolving approach that can assess all the environmental, social, and economic impacts of WtE to support the decision-making processes [8]. LCSA involves an incorporation of environmental Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (sLCA). LCA is a well-established tool used to assess the environmental impacts of a product, service, or process, taking into consideration the life cycle perspective [9], and has been used for assessing the environmental performance of various solid waste management options as indicated by Arena et al. [10]. LCC is an economic analysis method used to evaluate a service's total cost over its life span or period. It is a systematic approach that comprises all the costs of the infrastructure facilities incurred over the analysis period [11]. sLCA is less well-established compared to the other two components and is used to evaluate the actual and prospective, positive, and negative, social impacts through a life cycle [12]. Given that LCSA consists of the three sustainability dimensions, the tool allows for a more holistic understanding of the sustainability of products and processes, which in turn translates into better support for decision-makers [13]. Furthermore, LCSA provides the highest level of assessment among the existing sustainability tools, such as Cost Benefit Analysis (CBA) or Human Risk Assessment (HRA) [14].

As such, the research reported here sought to apply LCSA to assess WtE options for two major cities, Abuja, and Lagos, in Nigeria. The objectives were to identify in which of the two cities would WtE options be most sustainable and to see if there were differences between the two cities. The latter was hypothesised as being possible given their differences in terms of size, geography, history, and socio-economic status of the population and the potential impacts of these on waste collection and disposal processes.

Literature Review on LCSA

LCSA is a relatively new approach, and various researchers have suggested different frameworks for implementation. The LCSA literature is growing, but so far, there has been no consensus on a general framework for data collection, analysis, and interpretation. One of the key challenges with LCSA is the integration of the three components, as they comprise a variety of metrics as well as having different levels of maturity in terms of methodological development [13].

Furthermore, the presentation of results based on the objective of the study is a vital step to confirm the effectiveness of LCSA, but the addition of qualitative and quantitative indicators makes clarity and equivalence challenging [15].

There are some LCSA studies that have not attempted the integration of the three assessment tools into a single representation or 'score' for the overall sustainability assessment. Indeed, a recently published report from UNEP/SETAC (2020) did not recommend any combination and weighting of results of the three components due to the premature stage of LCSA study and application and because the individual objectives of each of the components are indirectly comparable.

There is also the issue of how to handle interactions and dynamic relations between indicators that could produce overlapping or double counting of certain effects, which is still not resolved. For example, the issue of indicators overlapping between sLCA and LCA was noted by Wulf et al. [16], especially in terms of human health and resource use.

Shrivastava and Unnikrishnan [17] conducted an LCSA of crude oil in India by proposing a framework that presented the results for all three life cycle attributes separately. Their study showed that for the environmental aspect, most of the emissions were generated from the oil refining and transportation phases. For the LCC, a new economic method had to be used due to the more complex operations of oil refineries. With respect to social aspect, it was discovered that the industries had created a solid association with their stakeholders, especially with the workers and consumers, and emphasised the need for improvement in various UNEP/SETAC (2020) subcategories such as 'Working hours', 'Equal opportunity', 'Health and Safety', 'Feedback Mechanism', 'Consumer Privacy' and 'End-of-Life Responsibility'. Similarly, Lu et al. [18] conducted an LCSA on the reusability of electrical and electronic products and components as partial steps towards improving Waste Electric and Electronic Equipment (WEEE) management policy in China. Their findings revealed that the reusability of the studied components was high, indicating their reuse is better than simple materials recovery, especially from the environmental and cost-benefit viewpoints as revealed by the LCA and LCC results. However, the sLCA results showed that it was difficult to determine whether job creation is more important than health risks or not, thus rendering the social aspect of reusability unclear. Nevertheless, the study concluded that component reuse should be encouraged.

In another study, Gulcimen et al. [19] performed an LCSA of a light rail transit system using a cradle-to-grave approach in Turkey. The results revealed that for the LCA, the global warming potential and abiotic depletion potential of the light rail system were 0.024 kg CO_2 eq. per passenger-km and 0.27 MJ, respectively, with a service life of 50 years, while the total life cycle cost of the light rail system was estimated at USD 0.046 for 1 passenger-km. The results also indicated that the main contributor to the total life cycle cost was energy at 92% (USD 2.88×10^8) of the total cost. In the sLCA, it was discovered that the industry had a better performance for society, the local community, and workers but had a weaker social performance for the consumer due to an ineffective feedback mechanism. Menikpura et al. [20] proposed a method known as 'broaden and deepen LCA' to perform an LCSA of managing MSW in Thailand. This approach refers to the inclusion of additional pillars of economic and social analysis and an additional method of impact measurement. Composite indicators were used to assess environmental, economic, and social sustainability, and damage to ecosystems and abiotic resources were regarded as measures of environmental sustainability, life cycle cost as economic sustainability, and damage to human health and community well-being as social sustainability.

All the examples mentioned above conducted their respective LCSA by representing the three life cycle attributes separately with no effort to combine them other than via a narrative. This primarily comes from the different levels of maturity of the three tools, with the LCA being by far the most developed, while sLCA is the least developed and needs much more research [21]. The integration of the three assessment tools within the LCSA framework remains a primary challenge [22] due, amongst other things, to the difficulty in maintaining constancy within the system boundaries and functional unit as well as the weights assigned to the three sustainability dimensions to combine the three assessment tools.

Several approaches have been taken to integrate all three assessment tools in LCSA. One approach is to use a scoring/ranking system for integrating the three components. For example, Kabayo et al. [23] used a ranking and scoring approach to integration with their LCSA of electricity generation systems in Portugal. They concluded that small hydro was the most environmentally and socio-economically sustainable system. Aziz et al. [24] also adopted a somewhat similar approach when using LCSA to evaluate the sustainability performance of a community composting system in Thailand that used waste from agro-industrial and agricultural processes to produce compost in granular and powder form. In this case, the impact assessment of the powder compost system (PCS) revealed that it had a 1.9×10^{-11} point impact on the environment, a 7238.75 THB (Thai Baht) economic impact, and a 3.33 scoring unit social impact. In contrast, the granular compost system (GCS) had a 2.1×10^{-11} point impact on the environment, a 9383.35 THB economic impact, and a 3.50 scoring unit social impact. Comparing PCS with GCS indicated that GCS had, respectively, a 1.1-, 1.3-, and 1.1-times greater influence on the environment, economy, and social elements than PCS. Overall, the LCSA results showed that GCS was found to be more sustainable than PCS.

Foolmaun and Ramjeawon [25] devised an LCSA technique based on the Analytical Hierarchy Process (AHP) to integrate the three assessment tools and ascertain which disposal method was the most sustainable for used poly-ethylene terephthalate (PET) bottles in Mauritius. This was applied to four disposal scenarios, with the findings showing that the scenario with 75% flake manufacturing and 25% landfilling was the most sustainable way to dispose of post-consumer PET bottles, whereas the scenario in Mauritius with 100% landfilling was shown to be the worst.

Vinyes et al. [26] employed a Multi-Criteria Approach (MCA) to integrate LCA, LCC, and sLCA in the LCSA of used cooking oil (UCO) waste management by classifying each indicator's metrics into one of three sustainability factors (SF): SFenviron., SFcosting, or SFsocial. To identify which strategies should be supported for the collection of UCO in Mediterranean cities, they used MCA to assess the sustainability of three domestic UCO collection systems: via schools (SCH), door-to-door (DTD), and via urban collection centres (UCC). The outcome showed that UCC offers the best alternative in terms of sustainability, followed by DTD and then SCH system, even if there are not many distinctions between DTD and SCH.

LCSA was also used by Tsambe et al. [27] to evaluate the sustainability of two Used Lubricating Oil (ULO) management systems in Brazil, and these included the transportation, trans-shipment, and re-refining phases (TTR) scenario along with the transportation, re-refining without the trans-shipment phase (TsTR) scenario. In this study, sustainability indices were used to help perform an integrated evaluation of sustainability, and these were calculated by aggregating data from a set of indicators. The results revealed that the TsTR scenario was the most sustainable of the two.

Other approaches, such Multi-Criteria Decision Analysis (MCDA), have been applied to combine the three facets of sustainability [28]. These methods span three main groups:

- Multi-Attribute Decision Making (MADM) methods, which are used to assess a limited set of options based on multiple criteria attributes;
- Multi-Objective Decision Making (MODM) techniques are used to point out and assess Pareto optimal solutions on the efficient frontier of a mathematically confined solution space;
- Data Envelopment Analysis (DEA), which has been employed to evaluate the relative effectiveness of a sample of alternatives if the efficient frontier is undetermined [29].

Atilgan and Azapagic [30] used MCDA for an LCSA of electricity generation in Turkey in order to determine the most sustainable options based on the assumption of various stakeholder preferences. The study concluded that hydropower was the most sustainable option for Turkey, followed by geothermal and wind electricity. Roinioti and Koroneos [8] used Muti-Attribute Value Theory (MAVT), related to MADM, as part of their LCSA of the Greek inter-connected electricity system for the sustainability assessment of the different electricity options. In their study, the trade-offs between environmental effects, costs, and social repercussions had an impact on which alternative was chosen as the most sustainable. When equal weighting was used for the three sustainability dimensions, wind energy was shown to be the electricity alternative with the best sustainability performance, as well as when the environmental and economic conditions were given priority.

However, due to the industry's significant employment implications, photovoltaics became the most favorable choice when the social aspect was considered a priority. Guo et al. [31] used MAVT to conduct an LCSA of pumped hydro energy storage in China. Their findings showed that, due to economies of scale, conventional pumped hydro energy storage

(CPHES) performed better in terms of economy and the environment than underground pumped hydro energy storage (UPHES), while UPHES performed better in terms of social sustainability due to the absence of stages of excavation and backfilling.

In the case of Nigeria, the use of LCSA for evaluating waste management systems' sustainability, particularly for WtE, is nonexistent. For instance, Ayodele et al. [32] only assessed the economic impacts of electricity generation from MSW using LCC, while Ayodele et al. [33] and Dunmade et al. [34] focused on environment and social assessments of electricity generation from MSW in Nigeria, using LCA and sLCA, respectively. Ogunjuyigbe et al. [35], on the other hand, focused on assessing the energy potential as well as determining the economic viability of potential WtE projects in selected cities of Nigeria. Other studies, such as Somorin et al. [36], only conducted a state-level assessment of the WtE potential in Nigeria, with findings showing that the electricity generation potential for the different states in Nigeria ranged from 31 to 205 MW, based on waste generation capacity of each state. Thus, the aim of the current study was to evaluate and compare four different prospective WtE systems for two key Nigerian cities (Lagos and Abuja) using an LCSA approach. As part of achieving this, this paper presents an LCSA framework comprising LCA, LCC, and sLCA to assess the environmental, economic, and social performance of WtE. The framework is directed at pointing out areas that need improvements for overall sustainability performance, and following the work of Kloepffer [37] and Finkbeiner et al. [14], the model can be summarised as:

$$\text{LCSA} = \text{LCA} + \text{LCC} + \text{sLCA} \tag{1}$$

LCSA = Life Cycle Sustainability Assessment
LCA = Environmental Life Cycle Assessment
LCC = LCA-type Life Cycle Costing
sLCA = Social Life Cycle Assessment

Equation (1) above proposes that the sustainability assessment of a product or a system should be performed by the application of the three life cycle techniques [38] followed by comparison and aggregation of their respective results using weighting [39]. The LCSA in this study involves an integration of the three sustainability dimensions (environmental, economic, and social) as reported independently for the WtE systems in [40–42]. The sustainability results for WtE in Lagos and Abuja are presented and compared with other studies, and the limitations that exist in integrating the three assessment tools are discussed, along with the implications for policy regarding the implementation of WtE in Nigeria. Suggestions for further work are made, particularly about potential improvements to the use of LCSA as an analytical tool for the sustainability of any system.

2. Materials and Methods

2.1. Lagos and Abuja

The choice of two cities, Lagos, and Abuja, for the LCSA of WtE in Nigeria, was based on the hypothesis that their differences in terms of geographic and socio-economic status may generate differences in the results for the WtE systems. Lagos is Nigeria's commercial centre, located in the southwestern part of the country. The city has a population close to 20 million [43], spans an area of approximately 3577 km^2 and has an average growth rate of almost 4% per year and a population density of 5032 people/km^2. Lagos has been identified as one of the metropolitan areas with the fastest growth rate globally [44], and the city generates waste at a rate of 0.72 kg/person/day, which equates to about 15,000 tonnes of waste each day [45]. Abuja, on the other hand, is the nation's capital city, located in the geographical centre of the country. Abuja forms part of the Federal Capital Territory (FCT) and covers a land area of 8000 km^2 with a population (in 2012) of 1,406,239 [46]. In 2014, the amount of waste generated monthly in Abuja was estimated to be approximately 30,000 tonnes, and this equates to an average per capita generation of MSW of about 0.66 kg/person daily [47]. Lagos is much older than Abuja, and the Atlantic Ocean hems the city on one side. The development of Lagos has been largely unplanned, with houses crowded densely together and streets usually narrow and clogged with traffic. As a result, Lagos's landfill sites are now encircled by dense urban settlements. Figure 1 indicates that Lagos has four official sites for the disposal of MSW in the city: Olusosun, Solous I, Solous II, and Abule-Egba, with ages ranging between 5 and 25 years and a combined capacity of 63.67 hectares with the Olushosun dumpsite being the largest of the sites covering about 42 hectares [45]. Abuja, however, has the benefit of being a planned city with wide streets set out in a grid form that eases transportation. The city's location in the geographical centre of the country means that there is abundant space for development, and the landfill sites are located outside the city. Figure 1 reveals that Abuja also has four disposal sites set aside for solid waste, although of these, only the Gousa landfill site is operational and is currently almost at full capacity [47].

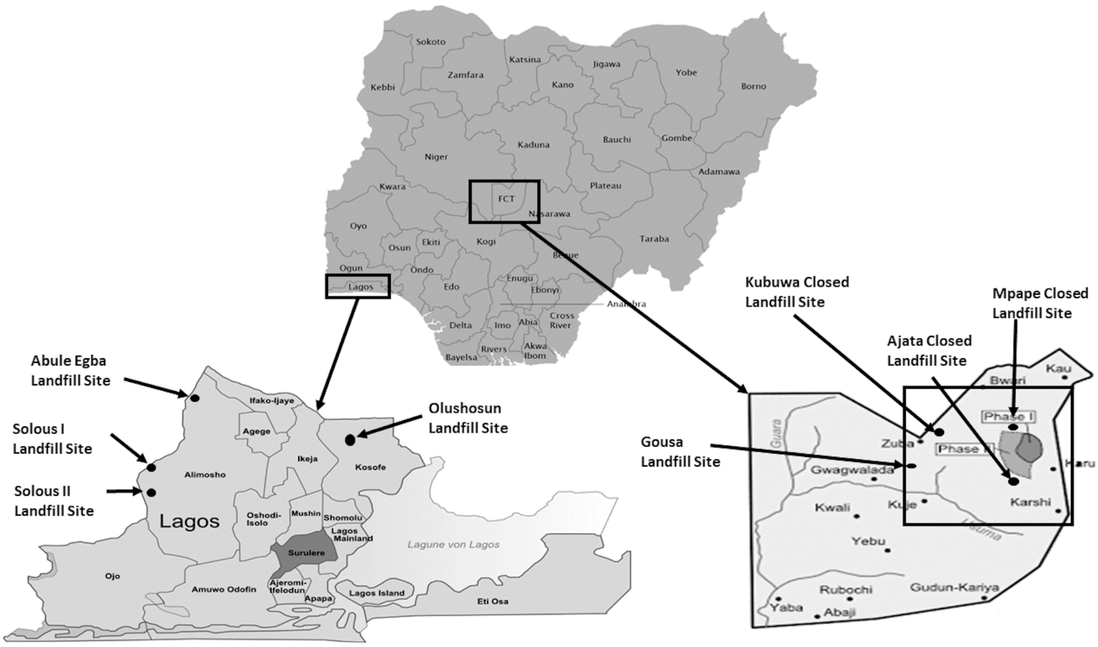

Figure 1. Map of the Lagos and Abuja metropolitan areas indicating their major landfill sites [48].

Despite their geographical and historical differences, both cities share the same challenges associated with rapid increases in population, increases in the amount of MSW generated, and issues associated with an inadequate electricity supply.

2.2. Data Collection

For the LCA, LCC, and sLCA, the detailed methodologies have been described by the authors in previous studies [40–42]. Therefore, to prevent repetition, only brief summaries of the methods and findings are provided here, with full detail available in [40–42]. Primary data were acquired from field observation, questionnaire-based surveys, and interviews, while secondary data were obtained from sources such as technical reports and relevant pieces of literature. The data required for the LCA were obtained from several sources such as technical reports, publications, personal communications from the staff of government authorities, the Ecoinvent database of SimaPro 9.0 software (manufactured by PRé Sustainability, Amersfoort, the Netherlands), and in some cases, calculations were made to estimate values such as fuel consumptions and air emissions. For the LCC, literature sources were used to obtain data on capital, operation, and maintenance costs, while data on disposal costs and revenues were acquired through face-to-face interviews. The data collection process for the sLCA began with participatory activities (Focus Group Discussion; FGD) held in Lagos and Abuja, followed by personal interviews and a questionnaire-based survey to acquire relevant data from key stakeholders such as site workers, managers, members of the local community and consumers. The type of data obtained ranged from quantitative, semi-quantitative to qualitative. Generally, the LCA and LCC required quantitative data, while sLCA needed semi-quantitative and qualitative information, which contributes to the challenge of aggregating various data types over the life cycle [49].

In terms of the relevant sustainability issues and indicators that pertain to the Nigerian waste and electricity sectors, these were identified using an extensive literature review. For the LCA, the environmental issues include those related to climate change (greenhouse gas emissions), resource depletion, and air, water, and soil emissions which were converted into 6 environmental indicators that were quantified using the CML impact assessment method (see Tables 1 and 2). In the case of the LCC, the key economic issue was that of electricity costs which was linked to the four indicators (Capital Costs, Operating and Maintenance Costs, Life Cycle Cost, and Levelised Cost of Electricity). The sLCA had 11 social issues which served as social impact subcategories (some of which included Employment and Health and Safety etc.); these led to 46 social indicators (some of which included Number of Jobs created and Level of expected Accidents/Injuries/Fatalities etc.), which were quantified using a 5-scale Likert system (see [40–42]).

Table 1. Overall LCSA Outcomes of WtE in Abuja using the Scoring and Ranking Approach.

LCA Abuja	**AD**	**Incineration**	**Gasification**	**LFGTE**
Abiotic Depletion Potential (ADP)	4	3	1	2
Global Warming Potential (GWP)	4	3	2	1
Human Toxicity Potential (HTP)	4	3	1	2
Photochemical Oxidation Potential (POCP)	2	4	3	1
Acidification Potential (AP)	4	3	2	1
Eutrophication Potential (EP)	4	3	2	1
Total Score	22	19	11	8
Average Score	3.67	3.17	1.83	1.33
Average LCA score for WtE	2.5			
LCC Abuja	**AD**	**Incineration**	**Gasification**	**LFGTE**
	1	4	2	3
Average LCC score for WtE	2.5			
sLCA Abuja				
Average sLCA Score for WtE	3.23			
Overall LCSA Sustainability Score	8.23			
Average LCSA Sustainability Score	**2.74**			

Box fill indicates ranking of impact: Dark Grey = Best Impact Category per WtE system, Light Grey = Worst Impact Category per WtE System.

Table 2. Overall LCSA outcomes of WtE in Lagos using the Scoring and Ranking Approach.

LCA Lagos	**AD**	**Incineration**	**Gasification**	**LFGTE**
Abiotic Depletion Potential (ADP)	4	3	1	2
Global Warming Potential (GWP)	4	3	2	1
Human Toxicity Potential (HTP)	4	3	1	2
Photochemical Oxidation Potential (POCP)	2	4	3	1
Acidification Potential (AP)	4	3	2	1
Eutrophication Potential (EP)	4	3	2	1
Total Score	22	19	11	8
Average Score	3.67	3.17	1.83	1.33
Average LCA score for WtE	2.5			
LCC Lagos	**AD**	**Incineration**	**Gasification**	**LFGTE**
	1	4	2	3
Average LCC score for WtE	2.5			
sLCA Lagos				
Average sLCA Score for WtE	3.97			
Overall LCSA Sustainability Score	8.97			
Average LCSA Sustainability Score	**2.99**			

Box fill indicates ranking of impact: Dark Grey = Best Impact Category per WtE system, Light Grey = Worst Impact Category per WtE System.

2.3. Components of LCSA and Their Integration

Two quantitative integration approaches involving aggregation of the results of the LCA, LCC, and sLCA into single scores were explored. They served as an overview representation of the comparative LCSA results of electricity generation from MSW in Lagos and Abuja. The first approach involved ranking and assigning a score to each WtE system within the LCSA impact categories along with a colour gradient scale. The second approach involves using MCDA based on MAVT, as it allows all three aspects of sustainability to be considered simultaneously, along with compensation among them [28].

2.3.1. Approach 1: The Ranking and Scoring System

Here, the total scores are estimated by summing up the WtE system's rankings in each of the LCA, LCC, and sLCA. For the LCA impact categories, a total aggregate score for each WtE system was derived by averaging the individual scores (equally weighted) for the six LCA impact categories assessed. The impact categories were ranked 1–4, with 4 being the best and 1 being the worst per WtE system for the LCA, LCC, and sLCA. A derived single score for the LCA is added to the single LCC and sLCA scores and averaged to derive an overall LCSA 'sustainability' score for WtE in the respective city. To minimise weighting bias, an average is taken of the scores for the individual environmental impact categories for the LCA of each WtE system, and then these are averaged to derive a single LCA score for the city. For the colour gradient scale, the most favourable option (score of 4) is highlighted in dark grey, while the least favourable option (score of 1) is highlighted in light grey. An example calculation for the LCA score is given below for AD (Lagos). All the scores for each impact category are summed and averaged by dividing by number of impact categories to obtain the score as follows:

$$\text{LCA score for AD (Lagos)} = \frac{4+4+4+2+4+4}{6} = 3.67 \quad (2)$$

This is added to the LCA score of the other three WtE systems (AD, LFGTE, and gasification) and then averaged to obtain a single LCA score for WtE (Lagos):

$$\text{LCA score for WtE (Lagos)} = \frac{3.67+3.17+1.83+1.33}{4} = 2.5 \quad (3)$$

A similar step was taken for LCC whereby the LCC values for each WtE are ranked and assigned score, which are summed up and averaged by dividing by number of WtE systems considered to obtain the LCC score for WtE (Lagos):

$$\text{LCC score for WtE (Lagos)} = \frac{4+1+2+3}{4} = 2.5 \quad (4)$$

Adding LCA and LCC scores to the sLCA single score and averaging it, the overall LCSA score for WtE (Lagos) is given as:

$$\text{LCSA score for WtE (Lagos)} = \frac{2.5+2.5+3.97}{3} = 2.99 \quad (5)$$

The same steps were taken for WtE (Abuja).

2.3.2. Approach 2: MCDA by Muti Attribute Value Theory

This approach estimates the overall sustainability score for each option as follows:

$$v(a) = \sum_{i=1}^{I} w_i \, v(a)_i \quad (6)$$

$v(a)$ = overall sustainability score
w_i = weight of importance for sustainability dimension i
$v(a)_i$ = score reflecting the performance of indicator for sustainability dimension i

I = total number of sustainability dimensions (i.e., 3; environmental, economic, and social)

From Equation (6), MCDA was performed in two steps to calculate the overall sustainability score for each WtE scenario.

The first step is to determine the scores for each sustainability dimension (environmental, economic, and social). This is dependent on the values of the related sustainability indicators determined in the sustainability assessment and their weights of relevance. Using the scores for the sustainability dimension calculated in the initial step and the weights of relevance for each dimension, the sustainability dimensions were used to work out the total sustainability score of the scenarios in the second step.

The MCDA was carried out with the assumption of equal importance for all the dimensions considering that equal weights are also assigned to indicators for each sustainability dimension to avoid bias (see Supplementary Materials). The MCDA was carried out under the assumption of equal importance for all the aspects considering that equal weights are also assigned to indicators for each sustainability aspect to prevent bias (see Supplementary Materials).

For the second approach, involving MAVT, the method assumed equal weighting for each sustainability dimension (w_i). Thus, equal weights of 0.33 were assigned to each of the three sustainability dimensions as follows:

$$\text{Weight of Dimension} = \frac{1}{3} = 0.33 \tag{7}$$

This was followed by assuming the best performance score to be 1, then the other scores were calculated as the proportion of the best sustainability performance for the WtE system; this was performed to standardise the indicators [31] (see Supplementary Material). For example, using Abiotoc Depletion Potential (ADP), where AD has the least ADP with a value of 0.6 MJ and standardising gives it a score of 1, making it the best in that category. The other scores were then evaluated as proportions of the best sustainability performance for the WtE system, as shown below:

$$\text{AD}: \ \frac{0.6}{0.6} = 1 \tag{8}$$

$$\text{Incineration}: \ \frac{0.6}{2.86} = 0.2097 \tag{9}$$

$$\text{Gasification}: \ \frac{0.6}{6.98} = 0.8595 \tag{10}$$

$$\text{LFGTE}: \ \frac{0.6}{3.63} = 0.1648 \tag{11}$$

This is repeated for all the other LCA impact categories and for all WtE systems. The values were then summed and averaged to derive the LCA score for each WtE system. The scores are then summed up and multiplied by the weight of the dimension to obtain the LCA score of WtE (Lagos), as shown below:

$$\begin{aligned} \text{LCA score for WtE (Lagos)} &= (0.8874 + 0.6590 + 0.4532 + 0.1817) \times 0.33 \\ &= 0.7199 \end{aligned} \tag{12}$$

This was also performed for the LCC single scores where incineration with the lowest LCC value was standardised to having the value of 1, making the option with the best performance, while scores of the other WtE were obtained as follows:

$$\text{AD}: \ \frac{214.1}{467.35} = 0.4581 \tag{13}$$

$$\text{Incineration}: \ \frac{214.1}{214.1} = 1 \tag{14}$$

$$\text{Gasification}: \frac{214.1}{411.04} = 0.5209 \tag{15}$$

$$\text{LFGTE}: \frac{214.1}{240.53} = 0.8901. \tag{16}$$

$$\text{LCC score for WtE (Lagos)} = (0.4581 + 1 + 0.5209 + 0.8901) \times 0.33 = 0.94680 \tag{17}$$

For the sLCA, the score obtained was multiplied by the assigned weight as follows:

$$\text{sLCA score for WtE (Lagos)} = (3.97) \times 0.33 = 1.3101 \tag{18}$$

The overall LCSA sustainability score for WtE (Lagos) was evaluated as:

$$\text{LCSA score for WtE (Lagos)} = 0.7199 + 0.94680 + 1.3101 = 2.977 \tag{19}$$

The same steps were followed for WtE (Abuja).

3. Results

This section presents the overall LCSA results using 'scoring and ranking' and MCDA methods of integration. The results compare the WtE sustainability performance for the two cities rather than a comparison of individual WtE systems.

3.1. Approach 1: Scoring and Ranking

The comparison of the WtE sustainability performance for the two cities using the Scoring and Ranking Approach to integration is given in Tables 1 and 2 for Abuja and Lagos, respectively. In both cities, AD exhibited the highest overall score since it had the lowest environmental impact for nearly all the impact categories, while LFGTE exhibited the lowest overall score as it had the highest environmental impact. Regarding LCC, incineration was the most sustainable from an economic perspective in both cities, while AD was the least sustainable. sLCA scores in Tables 1 and 2 apply to all the WtE technologies.

When summing up and averaging the LCSA scores by this ranking and scoring approach for the individual WtE systems for LCA and LCC, both cities achieved the same scores, indicating that the differences between the two cities did not influence the environmental and economic impacts of adopting WtE. However, this was different for the overall sLCA scores, which indicate that WtE offers a slightly higher level of social sustainability in Lagos than Abuja. The overall LCSA score revealed that the adoption of WtE would be slightly more sustainable in Lagos (2.99) than in Abuja (2.74).

3.2. Approach 2: MCDA by Muti Attribute Value Theory

The LCSA results using the MCDA approach for integrating the three dimensions of sustainability are given in Figure 2. The MCDA results are based on an equal weighting for the three dimensions. The total score for Lagos was 2.97, indicating a better overall LCSA 'performance' than Abuja (total score of 2.74). In both cities, environmental performance was essentially equal, but Lagos exhibited slightly higher scores in both the social (Lagos = 0.947; Abuja = 0.919) and the economic (Lagos = 1.31; Abuja = 1.07) dimensions. The results from the MCDA approach suggest that WtE would be slightly more sustainable in Lagos than Abuja, but the difference is small, and both cities exhibit very similar balances between scores across the three sustainability dimensions.

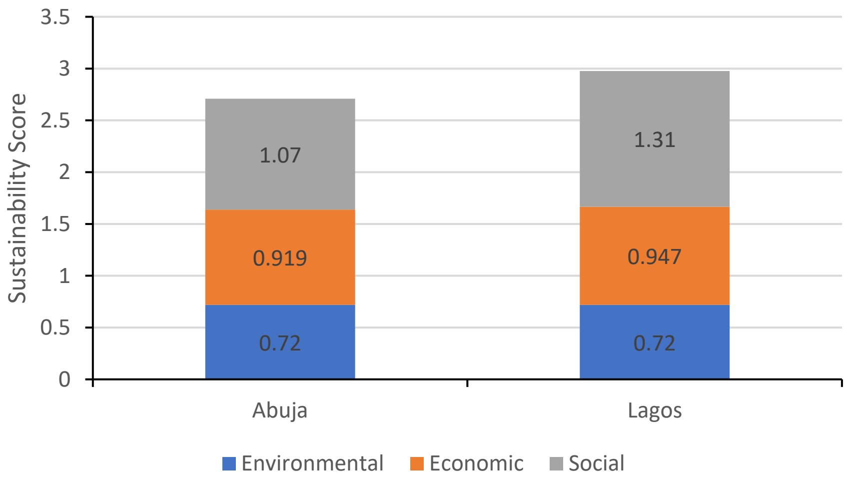

Figure 2. LCSA scores by the MCDA approach for the three sustainability dimensions for WtE in Abuja and Lagos.

3.3. Comparison of the Two Approaches to Integration

When comparing the results from the two approaches to integration, both shared similarities in terms of their social sustainability score being the highest of the three-sustainability scores. Likewise, the environmental sustainability score for both cities was equal using both approaches. However, the economic sustainability in the MCDA approach had Lagos scoring higher than Abuja, unlike the Scoring and Ranking approach, where economic sustainability scores for both cities were equal. This suggests the adoption of WtE would be more sustainable in Lagos (with a slight marginal difference between the two approaches) than in Abuja (where the scores from both approaches were the same). This could be attributed to the former having much more industry and population than the latter. Thus, it is anticipated that Lagos has a greater need for waste management and electricity than Abuja.

4. Discussion

4.1. Findings from the LCSA

LCSA was employed to assess the overall sustainability of generating electricity from MSW in Nigeria using four WtE scenarios with Lagos and Abuja as case studies. This is believed to be the first time that an LCSA has been implemented within such a context. The LCSA methodology, as applied to this present study, was useful for holistically considering and quantifying the broader life cycle impacts of WtE systems across the boundaries of traditional sustainability dimensions. The use of LCSA as a decision support tool has not only provided an outline of the prospective sustainability performance of generating electricity from MSW in Nigeria but has also highlighted areas of either considerable negative impacts where enhancements can be made or positive impacts where opportunities can be utilised [23].

In addition, the methodology points to the significance of the framework in considering the sustainability of any system. Given this, the results of the LCA were able to show that from an environmental perspective, AD was the most sustainable WtE system for both Lagos and Abuja. The LCC results revealed that incineration was the most sustainable option from an economic perspective for both cities. The sLCA result, although not considering the four WtE separately, showed that the adoption of WtE in general from a social perspective was more sustainable in Lagos than in Abuja. The LCSA was centered on aggregating the results of the three life cycle attributes into a single score using two approaches, and the results indicate that WtE would have slightly more sustainability 'benefit' in Lagos than in Abuja. However, it does need to be noted that data collection was challenging for the assessment of potential social impacts of the WtE technologies, and it is still unclear as to how social impacts should best be addressed and related to the functional unit.

Nonetheless, the similarity in the results from the two approaches adopted to integrate the scores of LCA, LCC, and sLCA suggests a degree of reliability in terms of the findings. This comes from the overall sustainability scores for both approaches being equal for Abuja (2.74) and almost equal, with a marginal difference for Lagos (Approach 1: 2.99 and Approach 2: 2.97). Due to the LCSA's comparatively early stage of development, there have been various challenges, specifically with regard to its constant operationalisation, making it difficult to obtain consistent and comparable results across research [13,15]. In fact, UNEP/SETAC (2020) does not propose any weighting or aggregation of the outcomes of the three methodologies. The results of the current study, however, indicate the need for standard approaches for integrating the LCSA results (indicators) specifically directed at the decision-making process as well as the requirement to thoroughly examine the interactions and trade-offs among the three dimensions of sustainability, a point also made by Hannouf and Assefa [50]. In addition, weighting presents another difficulty because all indicators can be mathematically integrated into one or few scores using weighted factors or ranked according to a weighting system. However, these approaches cannot be entirely based on scientific evidence but also rely on subjective judgement. As a result, numerous techniques, including surveys and expert panels (as well as online methods such as eDelphi), are available to offer weighting factors based on normative judgement, which is required as input for the aggregation step, but the problem lies in the fact that none of these factors are completely legitimised, which would be required if the resulting recommendations are to be adopted unequivocally by decision-makers. Additionally, trade-off situations do not become obvious, and decisions in such situations, which rely on weighting factors, may be challenging to appreciate and comprehend for those not participating in the study.

However, most decision situations do not need complete judgements, which can be best supported by a single score but are rather based on a more differentiated assessment [51].

The representation of sustainability for the WtE systems and contexts evaluated in the present research involved a 'dual' approach. In the first approach in this study, the assessment of results from the individual LCA, LCC, and sLCA tools was conducted separately (see [40–42]) and thus considers these dimensions of sustainability independently of each other. In the second approach, as presented in this paper, an integrated sustainability evaluation perspective was adopted by aggregating the results of the three life cycle analyses into an overall LCSA context, involving the derivation of single life cycle sustainability scores. The verification of many methodologies, either by the evaluation of the results in a distinct way or by aggregation, arose because of the absence of an agreed and consistent single methodology for integrated sustainability assessment [8]. Despite this, the present study has shown that valuable insights can be obtained from both individual life cycle-based approaches and from their aggregation into LCSA, and the somewhat different approaches to integration are complementary.

The use of the methodological approaches to LCSA described here has helped produce the sustainability impact results that could be presented to decision-makers/policymakers to allow them to have a better perspective of the WtE technologies under study. This comes from the identification of hotspot areas alongside preliminary points for potential areas of sustainability improvements. Additionally, the use of tools such as MCDA helped in creating new and better understandings to support the decision-making process through the aggregation of complex data from the various indicators that consider the different priorities of relevant stakeholders. For instance, the similarities in the scores suggest that both cities could derive equal 'benefit' from WtE. This implies that there is not a strong case, at least in terms of sustainability, for prioritising one city over the other. More cities could be evaluated by LCSA to see if this point has wider validity throughout the country. In addition, the selection of Lagos and Abuja has helped to point out the different sustainability impact perceptions for WtE, which can give useful insights for decision-makers and stakeholders in providing a sustainable route to address the dual issues of poor waste management and insufficient electricity supply. The approach taken here has also shown the benefits of identifying local specificities through the involvement of experts and stakeholders. This can be modified for other waste management strategies through the expansion of the system boundaries and the inclusion of key stakeholders. This means that the approaches used here can also be repeated in other places to find and evaluate the various sustainability impacts of adopting WtE technology and other waste management strategies. Given this, it is recognised that numerous opportunities remain for further studies to continue the development of LCSA approaches, especially with regard to the normalisation of a universal methodology for LCSA.

4.2. Political Implications of the Findings

In terms of policy implication and implementation, the present energy policy in Nigeria is primarily motivated by the urge to increase energy security. Hence, avoiding the problem of solving one issue (energy security or, indeed, waste management) at the expense of another (environmental or social impact, etc.) is something the government will be cognisant of when developing a sustainability plan for the electricity or the waste sectors. This will assist in making more sustainable decisions for the future. In addition, the government should implement a life cycle approach to decision- and policymaking. This will assist in identifying hotspots and prospects for lowering the environmental, economic, and social impacts across the whole electricity supply chains.

The government should encourage research into environmental improvements of WtE technologies as well as improve regulations to reduce environmental impacts from electricity generation. It is very important for the policy and decision-makers to resolve and execute the implementation of WtE policies that were intended to overcome the barriers and challenges from the perspective of finance, institution, and technology. Additionally, it is essential to adequately maintain and enforce a solid waste management policy in Nigeria to promote sustainable management of MSW, such as waste conversion to energy in Nigeria. According to Esae et al. [52], this enforcement of solid waste management policy in Nigeria will promote the adoption of various technologies used, such as those of AD, LFGTE, incineration gasification, and pyrolysis in generating energy from MSW in Nigeria.

4.3. Research Limitations

As noted above, one of the major limitations of this research was the lack of standardised approaches for integrating the LCSA results. In addition, the equal weight and importance assigned to sustainability dimensions and indicators in performing the overall sustainability assessment of WtE technologies is a challenge, as it requires decisions by the practitioner/researcher, often without a single objective justification or unambiguous theoretical basis. The LCSA results having several different indicators was another limitation in this study in potentially making the complexity of communicating the findings challenging. The fact that LCSA consists of different dimensions and each dimension comprises various stages and indicators, which could lead to several uncertainties, was another challenge to this research. Hence, this is part of the value of taking the LCSA to a single aggregated score as it makes it relatively straightforward to convey simple messages to policy makers, as drilling down deeper into the analyses helps identify and reveal details about the individual sustainability dimensions when time and interest is available. In terms of identifying and selecting the indicators, the challenges encountered included the difficulty in referring some of the indicators to the functional unit as well as verifying the indicator. One benefit of the participatory process in this present study was that stakeholders who have knowledge of the sector and its issues were involved in selecting the indicators. However, these stakeholders may not have selected indicators that represent the whole sector. It is important to ascertain that the selected set of indicators for the waste management and energy sectors are valid based on different benchmarks as well as on a wider range and larger number of stakeholders [53].

4.4. Future Research

Finkbeiner et al. [14] state that the aim of undertaking an LCSA is to help facilitate the sustainable development of any society, and this can only be achieved by it becoming both valid and applicable. Hence, more research is necessary to ensure consistency among environmental, economic, and social assessments. In addition, the benefits, and demerits of different operation research methods for interpretation and decision support in LCSA should be explored in more depth. Further improvements to the data could be made using more regionally specific and current data, as well as more comprehensive economic and social data. The application of advanced mathematical methods that can thoroughly deal with the uncertainties in an LCSA study should be further developed [1]. Further research on the integration of LCSA components using multi-criteria decision-making models and/or optimisation models should be made in the future. Lastly, more research into sLCA is needed to enhance the methodology and agreement for characterisation and comparison between indicators. Additionally, effective, and efficient methods to show the LCSA results to decision-makers are required to address the aspect of the trade-off between validity and applicability. This is essential as it serves as a criterion for properly communicating the LCSA results to decision-makers.

5. Conclusions

The following conclusions regarding the comparative sustainability performance of prospective WtE systems for Lagos and Abuja in Nigeria are taken from this study:

- The LCA results revealed that AD was the most sustainable alternative for both Lagos and Abuja from an environmental perspective.
- The LCC results indicated that incineration was the most sustainable option from an economic perspective for both cities.
- The sLCA result revealed that the adoption of WtE in general, from a social perspective, was more sustainable in Lagos than in Abuja.
- The integration of the results from the three assessments used in the LCSA gives the overall sustainability performance; hence, the LCSA results indicate that the introduction of WtE had slightly higher sustainability 'benefit' in Lagos than in Abuja.
- The ranking and scoring approach generated sustainability scores of 2.99 and 2.74, while those from the MCDA approach were 2.97 and 2.74 for Lagos and Abuja, respectively.
- Based on both approaches to integration, the sustainability score associated with the adoption of WtE in Lagos (2.99 and 2.97) would be approximately 8–9% higher or more sustainable than it is for Abuja (2.74).
- LCSA methodology in this current study was useful in calculating the broader life cycle impacts of the WtE systems across the boundaries of conventional dimensions of sustainability.
- LCSA can serve as a decision support tool to provide an outline of the sustainability performance of the current and future waste management and electricity generation systems used in Nigeria and other developing countries by highlighting areas of the negative impact that will require improvements and those of positive impact where opportunities can be exploited.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en15239173/s1. Table S1: Overall Sustainability of WtE in Abuja using a Scoring and Ranking Approach; Table S2: Overall Sustainability of WtE in Lagos using a Scoring and Ranking Approach; Table S3: The Overall Sustainability Performance of WtE (Lagos); Table S4 The Overall Sustainability Performance of WtE (Abuja); Section S1: Approach 1: The Ranking and Scoring System; Section S2: Approach 2: The Muti Attribute Value Theory.

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