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Electricity Generation from Municipal Solid Waste in Nigeria: A Prospective LCA Study

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Abstract: Diverse opportunities and environmental impacts could occur from a potential move towards waste-to-energy (WtE) systems for electricity generation from municipal solid waste (MSW) in Lagos and Abuja, Nigeria. Given this, the purpose of this study is to use life cycle assessment (LCA) as a primary analytical approach in order to undertake a comparative analysis from an environmental impact perspective of different WtE scenarios, along with diesel backup generators (DBGs) and grid electricity. A functional unit of 1 kilowatt-hour of electricity produced was used in assessing the following environmental impact categories: abiotic depletion (fossil fuels) potential (ADP), global warming potential (GWP 100a), human toxicity potential (HTP), photochemical oxidation potential (POCP), acidification potential (AP), and eutrophication potential (EP). The overall result indicated that anaerobic digestion (AD) had the highest energy generated per one tonne of MSW processed for both Lagos (683 kWh/t) and Abuja (667 kWh/t), while landfill gas to energy (LFGTE) had the lowest for both (Lagos 171 kWh/t, Abuja 135 kWh/t). AD also had the lowest environmental impacts amongst the four WtE systems for both cities based on all the impact categories except for POCP. In contrast, LFGTE had the highest impact in all the categories except ADP and HTP. Extending the analysis to include diesel-based generators (DBG) and grid electricity saw the DBGs having the highest impact overall in ADP (14.1 MJ), HTP (0.0732 Kg, 1.4 DB eq), AP (0.0129 Kg SO_2 eq), and EP (0.00313 Kg PO_4 eq) and grid electricity having the lowest impact in GWP (0.497 Kg CO_2 eq), AP (0.000296 Kg SO_2 eq), and EP (0.000061 Kg PO_4 eq). It was concluded that additional electricity supply from AD to the grid, with its potential to reduce the reliance on DBGs (worst scenario overall), would be a positive action in environmental impact terms.

Keywords: waste-to-energy; municipal solid waste; waste management; electricity supply; life cycle assessment; environmental impacts; diesel backup generators; grid electricity

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1. Introduction

Globally, the trend towards rising levels of industrialization, urbanization, and economic growth has contributed to the increase in the quantity of municipal solid waste (MSW) [1]. According to Kaza and Lisa [2], the annual generation of MSW exceeds 2 billion tonnes (as of 2016). This is expected to rise in the coming years with the population projected to be approximately 9.7 billion by 2050 [3]. Presently, only about 38% of the MSW generated is effectively managed, through either sanitary landfills, recycling, or energy recovery, while the rest is managed in an unsustainable manner, resulting in environmental challenges [3]. The poor management of this waste has led to many environmental issues, such as global warming, ozone depletion, human health hazards, abiotic resource depletion, and ecosystem damage, among others [4]. Khan et al. [5] also indicated that solid waste generation and treatment could lead to pollutants being emitted into the air, land, and water, which could result in climate change and have a severe impact on human and environmental health. These hazards emanate from toxic waste dumping, the use of non-biodegradable materials, the release of harmful greenhouse gases, the disposal of sludge, and the waste of other dangerous chemicals [6]. An example is seen in the case of biosolids such as municipal sewage sludge, which contains toxic elements, such as Cd, Zn, Cr, Ni, and Pb, that contaminate the soil and, when eventually released into water and ground water, can cause damage to natural ecosystems, and negatively affect human health by biomagnification within food sources [7]. Another example is wastewater, which is contaminated water that ought to be treated before being released into rivers and lakes to avoid further groundwater pollution. In addition, there is the emergence of new contaminants, such as those from pharmaceutical and cosmetic industries, that have uncertain effects but the potential to generate significant harm to human health and the environment [8]. These emerging contaminants are dumped into natural environments, either intentionally or unintentionally, with or without regulated treatments [9]. The mitigations of the environmental and human health risks posed by these pollutants require innovative, applicable, and feasibly economic methods for sustainable management, such as various remediation and decontamination procedures, along with an integrated waste management system. Given all these issues, this explains why sustainable waste management has become a topic of interest in many countries [4].

Another issue confronting the world, especially in developing countries, is the finding of sustainable energy sources. The world energy consumption is expected to rise by 44%, from 1.38×10^5 TWh in 2006 to 1.97×10^5 TWh in 2030, with carbon dioxide (CO_2) emissions also projected to increase by 39% from 29 billion tonnes to 40.4 billion tonnes between 2006 and 2030 [10]. According to Wang et al. [11], this situation could soon lead the world into a severe energy crisis. The increase in population has resulted in an increasing global energy demand due to the depletion of non-renewable sources and the need to address the problem of climate change [10]. In addition, environmental pollution, and its negative impact in terms of climate change, could also create changes in the fundamental social and environmental factors determining global health, a large part of which can be attributed to the combustion of fossil fuels, along with agricultural activities and land use changes [12]. As a result, researchers are currently searching for alternative energy sources to help deliver energy-saving and environmental-protection provisions for development [13,14]. One such strategy is to use MSW to generate energy (in the form of electricity); this is referred to as waste-to-energy (WtE) technology. The adoption of WtE can potentially serve as a sustainable platform for simultaneous waste management and energy provision [15–17] by providing an alternative pathway to that of extremely poor waste management, whilst also contributing to meeting the energy demand. WtE technologies can generally use either thermal (incineration, gasification, and pyrolysis) or biological (landfill gas to energy and anaerobic digestion) systems to extract usable energy stored in MSW to produce heat, electricity, or both (combined heat and power) [18]. Rogoff and Screve [19] noted that there are about 2179 WtE facilities worldwide, most of which are situated in Asian countries such as Japan, China, Taiwan, and Singapore, where they are faced with open space issues for landfilling and dense urban populations.

As part of assessing the environmental sustainability of WtE, the life cycle assessment (LCA) is a widely used approach [16]. The LCA has been employed for assessing the potential environmental impacts of WtE using several standards and methods such as Eco-indicator 99 and CML 2001, with software such as GaBi, SimaPro, openLCA, etc. [20–22]. In addition, LCA forms a core component of the life cycle sustainability assessment (LCSA), which is attracting much attention as it seeks to combine LCA, life cycle costing (LCC), and social life cycle assessment (sLCA) within a unified assessment [23]. Several LCA studies have explored the options for sustainable waste management and energy recovery [15,24,25]. Arena et al. [15], compared the LCA impacts of residual MSW treatment through gasification and incineration technologies, indicating that incineration has a lower environmental burden than gasification in most of the selected impact categories for the European composition of residual MSW. Dong et al. [24], compared the LCA of MSW gasification and incineration in China, Finland, and France, and the results indicated that the gasification of MSW in Finland has lower levels of environmental burden compared with the incineration of MSW in China and France for all seven assessed impact categories. The comparisons of these WtE technologies showed that the technology preferences for the least environmental impact can depend to a large degree upon local circumstances and context.

Along with many developing countries, Nigeria is confronted with the challenges of a weak waste management system and an inadequate electricity supply. This comes from the country having an estimated population of approximately 200 million people, producing about 32 million tonnes of MSW annually (0.438 kg/person/day), with only a 20–40% formal waste collection rate [26]. Furthermore, the average per capita electrical energy consumption in Nigeria is 144 kWh per annum, while the power generation installed capacity of the national grid in 2017 was 12 GW [27]. These are well below those of other developing countries such as, e.g., South Africa (3591 kWh, 47 GW) and Indonesia (609 kWh, 53 GW) for the same year. Given this, the substantial power deficit for Nigeria suggested by [27] comes from the fact that even with the power generation installed capacity of 12 GW (with only 5.5 GW being available), the supply availability is clearly a far cry from the electricity demand (approx. 40 GW), as stated by [28]. The unreliability of Nigeria's power grid in providing constant and adequate electricity has been a major reason for the widespread use of diesel backup generators (DBGs) by both households and businesses [29]. However, the use of these DBGs has contributed to regional and local air pollution [30], resulting in air quality deterioration and adversely affecting human health [31]. These emissions include particulate matter (PM), nitrogen oxides (NO_x), carbon moNO_xide (CO), and sulfur dioxide (SO_2) [32] and are known to contribute to acid rain, global warming, and ozone layer depletion [33].

Adopting WtE technologies is a potentially viable option that could help address the twin concerns of how to improve MSW management and the electrical power supplies in Nigeria. Indeed, this forms a key part of the objectives of the National Energy Policy and the National Policy on the Environment, which were created, respectively, to encourage renewable energy resources as well as to decentralize the energy supply to ensure that 75% of the population has access to electricity and to secure an environmental quality that is adequate for the health and wellbeing of Nigerians [34]. However, selecting suitable WtE technology for a developing country such as Nigeria depends on several factors, such as technological efficiency, economic benefit, and social and environmental acceptability. There is a lack of concrete scientific information that could encourage WtE development in the country [27]. Consequently, the understanding of such technologies starts with knowing how their input and output flows affect their overall environmental performance [10] and accounting for the differences between the WtE options in terms of both their energy conversion rates and their emissions [35].

In Nigeria, very few studies have been conducted on the use of the LCA in MSW management, particularly WtE, compared with the number that have been performed in several other parts of the world. For instance, Ayodele et al. [36] used the LCA to assess the environmental impact of WtE technologies for 12 cities in Nigeria to determine the option best suited for the various locations. They found that a hybrid of incineration/AD was the best option overall in terms of GWP and AP, while LFGTE technology was the best in terms of carcinogenic reduction potential. However, this study considered only three impact categories: GWP, AP, and dioxin/furan emission potential (which is not a classical LCA impact category). It also did not seek to make a comparison between the impacts of these technologies and those from grid electricity or DBGs. Given this, there is a clear gap in knowledge on the environmental impact assessment of WtE technologies in Nigeria, especially when compared with grid electricity and DBGs. As such, more work is required on the environmental impacts of WtE in the Nigerian context given the current state of MSW and electrical power management in Nigeria.

The present research aims to address this gap by using an LCA approach to explore and assess the potential environmental impacts of the WtE options and to compare them with those of grid electricity and DBGs for two urban areas (Lagos and Abuja) in Nigeria.

Four globally well-established WtE systems (incineration, AD, gasification, and LFGTE) were modelled. Unlike previous LCA studies on WtE, such as that of Ouedraogo et al. [37], which focused on the technology as a means of waste management by using a functional unit on a mass basis of MSW, the research described here set out to analyze WtE by considering electricity production as a primary function. Taking such an approach allows for a comparison with the other electricity generation options mentioned above whilst considering waste management as a co-product. As part of this analysis, the results are reported without aggregating the relative negative emissions from the avoidance of landfilling along with the avoided emissions from offsetting fossil fuel-based electricity. Thus, a functional unit of 1 kWh of electricity produced was selected to reflect the intended function of electricity generated by the WtE systems. This approach is related to that of Pfadt-Trilling et al. [38], who used LCA to assess the climate change impacts of electricity generated at a WtE facility. In addition, this research presents not only a prospective LCA on WtE in general but can also be integrated into the larger framework of LCSA to help guide the decision making on integrated environmental, social, and economic grounds.

2. Materials and Methods

2.1. Study Locations: Lagos and Abuja

The WtE options were explored for two major urban centres in Nigeria, Lagos and Abuja. These two cities were selected as it was hypothesized that their somewhat different characteristics might yield different LCA results for the WtE options. The cities, with their growing populations, are strategically important in Nigeria (Figure 1), the former being the country's commercial capital and the latter being the seat of the federal government. They differ from each other in geographic and socio-economic perspectives, with Lagos being an older city with an uncoordinated urban expansion and transportation system and Abuja being a more recently developed (1970s) and better planned and laid out city, following a grid system of major roads and a zoning of activities (housing, retail, offices etc.). Lagos has a higher population size, and its dwellings are packed densely together with narrow streets congested with traffic.

The main dump sites in Lagos, such as the Abule-Egba landfill site, the Olushosun landfill site, and the Solous I and II landfill sites [39], are surrounded by dense urban development, almost reaching their proposed maximum capacity. The dump sites in Abuja, such as Mpape, Ajata, Kubwa (all three closed in 2005), and Gousa, as indicated in Figure 1, are outside the city [40]. Thus, when planning the study these differences were considered to be of potential importance in the inputs and outputs of the MSW systems and therefore the possible LCA results for the WtE systems and their grid electricity and DBG comparators.

Lagos is a located on the southwestern coast of Nigeria, covering a land area of 3577 km^2 and with a population of approximately 21 million people. The city serves as the primary commercial centre of Nigeria [41]. The city generates waste at 0.72 kg/person/day, which is approximately 15,000 tonnes daily [42]. With a population growth rate of 3.26%, the quantity of waste is expected to keep increasing [43]. Lagos also has many production and service industries in the formal and informal sectors that account for more than 70% of the city's urban economy [44], generating a significant amount of waste. Abuja is the capital city of Nigeria, situated at the centre of Nigeria, in the Federal Capital Territory (FCT), within the latitudes of 7°25′ N and 9°20′ N and the longitudes of 5°45′ E and 7°39′ E. The city has a landmass of about 7753.85 km^2, with an estimated population of approximately 2,238,800 people [45]. Abuja, like Lagos, is one of the fastest-growing cities in Nigeria; as a result, various activities have contributed to the increasing quantity of MSW in its environs. In a report by the Abuja Environmental Protection Board (AEPB) in 2015, the amount of MSW generated in 2001 was 41,402 tonnes, which practically increased to 353,717.41 tonnes in 2014, with an average per capita generation of MSW estimated to be at 0.66 kg/person daily [46].

As with many cities in Nigeria, there is a need for both Lagos and Abuja to effectively and efficiently manage the MSW generated [47]. As such, both cities, through their respective agencies—the Lagos State Waste Management Authority (LAWMA) and the AEPB—have taken various steps to address waste management issues in both cities through their private sector participation (PSP) programmes that see the former collecting waste from public areas, with private companies collecting waste from residential and commercial areas [42], while the latter allots districts to many individual companies for waste collection and transportation [48]. In addition to their waste management issues, both cities face the challenge of inadequate public electricity supply. This is seen with the electricity demand in both cities outweighing the current public supply [49]. The acute shortfall in energy supply in both cities leaves their inhabitants with just 1 to 5 h of electricity daily [50]. The outcome is that many households, companies, and industries have resorted to purchasing and using standby diesel generators as part of the attempts to bridge this gap in supply by using alternative sources such as diesel generators [51]. Given this, Ogunmakinde et al. [52], noted that the adoption of WtE could have the potential to generate sufficient electricity to power over 11,000 and 94,000 homes in Abuja and Lagos, respectively, as well as facilitate improved waste management. However, the adoption of such strategies is challenged by inadequate funding and the absence of political will from the government [53].

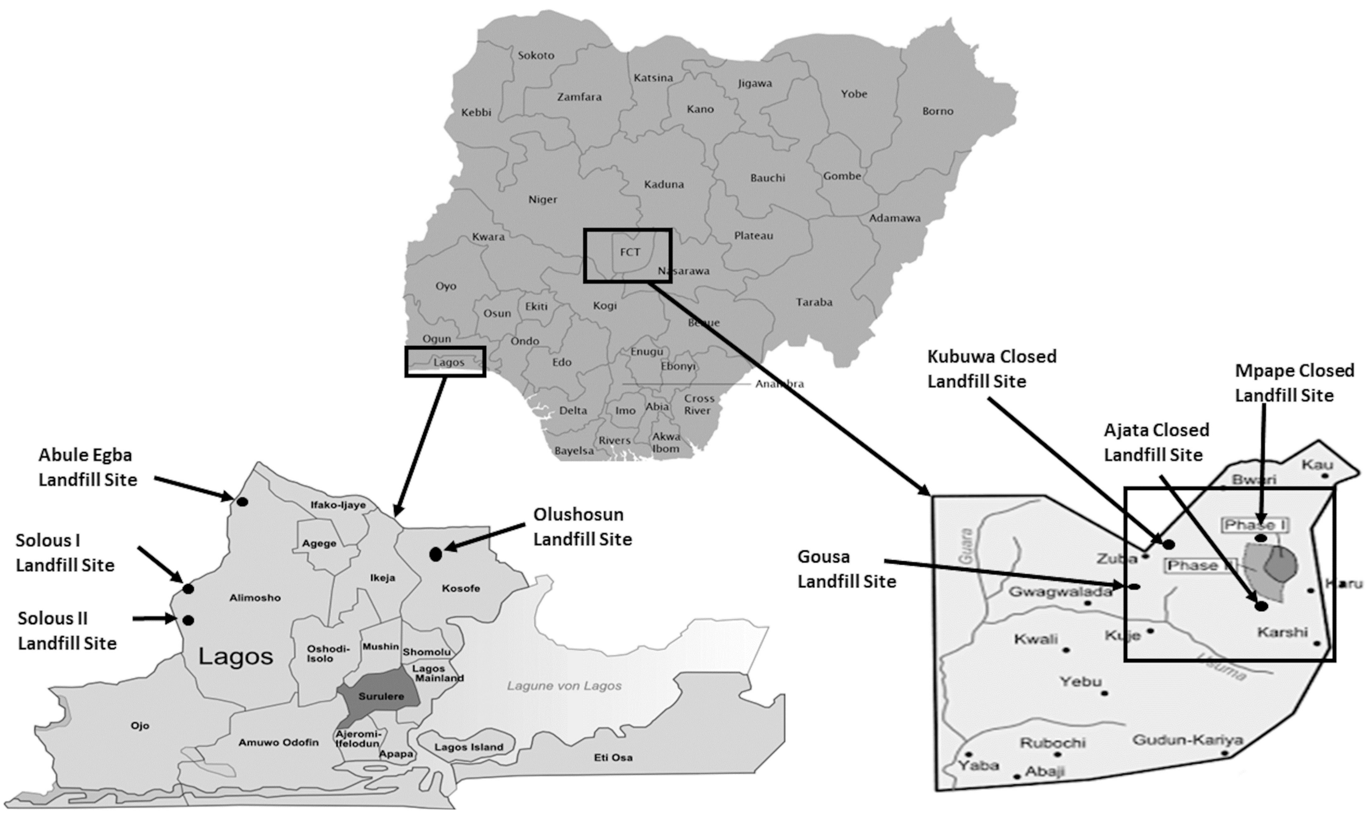

Figure 1. Map of the Lagos and Abuja metropolitan areas indicating their major landfill sites [54].

2.2. Development of WtE Scenarios

The development of the WtE scenarios for the LCA was based on the composition of the collected MSW for Lagos and Abuja (Table 1). Almost 50% of the waste of both cities is food waste, with the remaining waste consisting of plastics, paper, textiles, glass, and metals.

Table 1. The MSW composition of Lagos and Abuja [46,55] (compiled by the authors).

Waste Components	Lagos	Abuja
	(%)	(%)
Food Waste	46	47
Paper	13	14
Plastics	23	22
Textiles	12	5
Metal	2	7
Glass	4	5
Total	100	100

For this study, food waste was classified as 'putrescible'; paper, textiles, and plastics were assigned as 'combustibles' and metals and glass as 'recyclables'. The scenarios for this study were as follows:

Incineration WtE Scenario: In this scenario, the combustibles portion of the waste in both cities (Lagos: 48% and Abuja: 41% by mass for 1 tonne of MSW) is sorted and sent to the incineration plant where it is combusted to produce electricity with solid residues (ash) being diverted for alternative uses in road and building construction sites. This refers to the bottom ash generated from the incinerator, which was taken as 15% of the combustibles portion of the 1 tonne of MSW (Lagos: 0.072 tonne and Abuja: 0.0615 tonne), while the fly ash was 3% of the combustibles portion of the 1 tonne of MSW (Lagos: 0.014 tonne and Abuja: 0.0123 tonne) for the present study [56]. The food waste and recyclable portions of the MSW are not a feedstock for this scenario; the food waste is assumed to be sent to AD (where it is used to generate electricity and digestate, which are not included in this incineration scenario), and the recyclables are sent to the recycling facility (also excluded from the incineration scenario).

AD WtE Scenario: This involves the separation of the food waste (Lagos: 46% and Abuja: 47% by mass for 1 tonne of MSW) from the rest of the MSW and its transfer and use in AD plants to produce biogas for combustion for electricity generation and digestate. It is assumed that the digestate is used as a fertilizer (which is not included in the AD scenario), while the remaining waste fractions (the combustibles and recyclables) are assumed to be used for electricity generation via incineration and recycling (also excluded from this AD scenario).

Gasification WtE Scenario: All the waste except the recyclables (Lagos: 94% and Abuja: 88% by mass for 1 tonne of MSW) is used for energy recovery after the sorting process. Thus, energy via gasification is recovered from the food waste and combustible fractions, the residues from the gasification are assumed to be used as construction material, and the recyclables go to recycling.

LFGTE WtE Scenario: This scenario involves all the collected MSW being placed in managed landfill without any sorting. The landfill gas is collected, treated, and combusted for electricity production (and the remaining material stays in the landfill indefinitely).

Grid Electricity Scenario: This scenario considers the environmental impacts of the use of grid electricity in Nigeria. The electricity grid generation mix for Nigeria was taken as being derived from natural gas: 86% and hydro: 14% [57].

DBGs Scenario: This scenario considers the environmental impacts of using electricity from DBGs as alternatives to grid electricity. This is because the grid in Nigeria is insufficient to serve the needs of the country and the massive population and economy of Nigeria [51].

Overall Assumptions: The following general assumptions have been made for all the LCA scenarios:

- The sorting facility and WtE plants were co-located. As a result, the transport distances for MSW for all the WtE scenarios are the same.
- It is assumed that the electricity produced from WtE is not an avoided product and no 'avoided burden' credit (e.g., against grid electricity or DBG generation) is applied.

- The environmental impacts from the digestate and solid residues are not considered in this study.
- The separation of recyclables such as glass and metals from the MSW occurs at the sorting facility into various categories which leave the WtE systems and are not modelled further in the LCA.

2.3. LCA

The LCA is a standardised approach under the International Standards Organisation (ISO), ISO 14040 and 14044. It follows four phases: (i) goal and scope, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation.

2.3.1. Goal and Scope

The goal of this LCA was to assess and compare the environmental impacts of the potential implementation of WtE in two major cities in Nigeria using four different WtE systems. The functional unit (FU) for the LCA was:

> *"The production of 1 Kilowatt-hour (kWh) of electricity produced from collected MSW by various WtE systems."*

The study applied this FU specifically to Lagos and Abuja under the system boundary illustrated in Figure 2. The system modelled begins with MSW collection and transportation, the sorting of the MSW, and its processing via four WtE technology systems. It includes the required inputs (e.g., operational power demand, fuel consumption for transport, etc.) for the electrical power output (1 kWh) and the associated emissions.

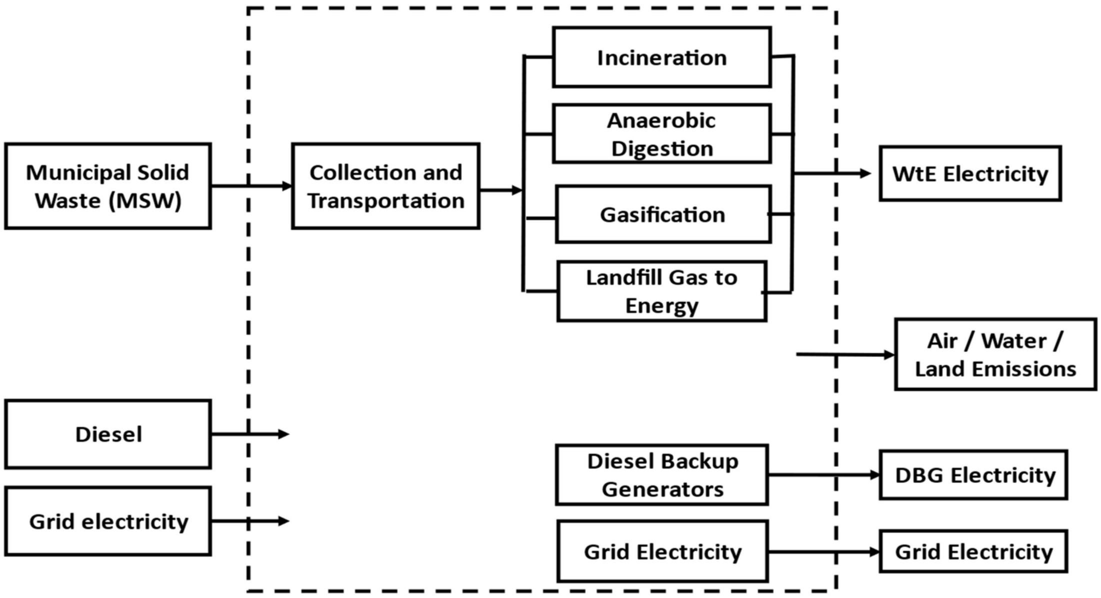

Figure 2. System boundary for the WtE LCA for Lagos and Abuja (with the inclusion of DGB and grid electricity.

2.3.2. Life Cycle Inventory (LCI)

The LCI data were assembled from technical reports, publications, personal communications from the staff of the waste management authorities, and on-site investigations. The data on the collection and transportation of the MSW were obtained from the staff of the LAWMA and the AEPB. Site-specific data on incineration, AD, gasification, and LFGTE were not available for Lagos and Abuja, and so, these data were obtained from the relevant literature. Likewise, the data on diesel fuel and electricity consumption were also obtained from the relevant literature whilst the data for the emissions and electricity generated from the WtE systems were obtained from calculation with the remaining datasets obtained from the Ecoinvent database. It should be noted, however, that there were some inconsistences in the emissions datasets due to the absence of relevant data, especially for some of the WtE systems. The full inventory data and sources are given in Supplementary Materials. Table 2 provides a summary of the electricity consumption for the different WtE systems. The conversion efficiencies obtained from the literature were 26, 20, and 33% for AD, incineration, and LFGTE, respectively [36], while for gasification it was 23% [58]. Table 3 gives the data on their energy output. Table 4 gives an aggregated set of all the emissions data for the different WtE systems. For the grid electricity, the medium-voltage electricity mix for Nigeria from the Ecoinvent v3 database was used—this is based on the electricity grid mix in Nigeria in 2018 (natural gas: 86% and hydro: 14%), according to [59].

It should be noted that these same data for the grid mix were used where relevant for the operational electricity demand of the WtE processes (i.e., the electricity generated by the processes themselves was all assumed to be available for despatch and was not taken for 'parasitic' demand for process operations). Thus, the data for the electricity consumption for the sorting process were obtained from the literature and taken as 3.2 kWh/t [60], while the values of the diesel consumptions for the landfill operations and DBG were given as 3 L/t [61] and 3.2 L/kWh [62], respectively. The diesel consumption of 80 L per roundtrip for waste collection and transportation of 9 tonnes of MSW was derived from consultation with the staff of the LAWMA and AEPB, giving 8.8 L diesel/t MSW.

Table 2. Operational electricity consumption for the WtE Systems.

WtE Systems	Electricity Consumption (kWh/t of Waste Processed)
AD	7.7 [60]
Incineration	77.8 [63]
Gasification	339.3 [63]
LFGTE	14.3 [63]

Table 3. Electricity generated from WtE systems.

Electricity Generated (kWh/t of Waste Processed)	Abuja	Lagos
AD	667	683
Incineration	441	549
Gasification	639	625
LFGTE	135	171

Table 4. Emissions for WtE systems for Abuja and Lagos.

Emissions (Kg/t of Waste Processed)	Incineration	
	Abuja	Lagos
CO_2 biogenic	519.3	604.2
CO_2, fossil	255.8	297.6
CO	0.11	0.13
N_2O	0.0045	0.0053
NO_x	0.45	0.53
NH_3	0.009	0.011
Non-methane organic compounds (NMVOC)	0.011	0.013
	AD	
CO_2, biogenic	31.2	28.9
CH_4	11	11.3
NH_3	0.654	0.649
H_2S	0.08	0.04
	LFGTE	
CO_2, biogenic	122.2	143.1
CH_4	44.7	52.1

Table 4. *Cont.*

Emissions (Kg/t of Waste Processed)	Incineration	
	Abuja	Lagos
	Gasification	
CO_2, biogenic	589.6	629.8
CO_2, fossil	290.4	310.2
NO_x	0.67	0.73
SO_x	0.046	0.05
HCl	0.028	0.03
Mercury (Hg)	0.00006	0.00007
Arsenic (Ar)	0.00005	0.00006
Nickel (Ni)	0.000035	0.00004
Cadmium (Cd)	0.000006	0.000007
Volatile organic compounds (VOC)	0.0097	0.01
HF	0.00029	0.0003

2.3.3. Life Cycle Impact Assessment (LCIA)

The LCIA was conducted using the CML-IA method for the six impact categories (see Table 5) selected for the main presentation of the results: ADP, GWP, HTP, POCP, AP and EP [60]. These categories were selected as the most appropriate to represent a range of relevant impacts associated with such energy-generating processes. The full range of 11 impact categories in the CML-IA method was assessed as part of the LCIA and the data for all these are given in Supplementary Materials, Tables S7 and S8.

Table 5. Life cycle characterisation results for the WtE systems, DBGs, and grid electricity per 1 kWh of electricity for Abuja and Lagos [CML-1A impact assessment method].

Impact Category	Unit	AD	Incineration	Gasification	LFGTE	DBGs	Grid Electricity
ADP (Fossil Fuels)	(MJ)	**0.62 (A)** 0.6 (L)	**3.17 (A)** 2.86 (L)	6.40 (A) **6.98 (L)**	**4.59 (A)** 3.64 (L)	14.1	8.67
GWP	(Kg CO_2 eq)	**0.507 (A)** 0.506 (L)	**0.80 (A)** 0.74 (L)	0.86 (A) **0.94 (L)**	**9.5 (A)** 8.7 (L)	1.02	0.497
HTP	(Kg 1.4 DB eq)	**0.0055 (A)** 0.0054 (L)	**0.0102 (A)** 0.0092 (L)	0.0195 (A) **0.0213 (L)**	**0.019 (A)** 0.015 (L)	0.0732	0.0117
POCP	(Kg C_2H_4 eq)	0.00011 (A) 0.00011 (L)	**0.0000396 (A)** 0.0000357(L)	0.0000464 (A) **0.0000506 (L)**	**0.00202 (A)** 0.00186 (L)	0.000198	0.0000406
AP	(Kg SO_2 eq)	**0.000564 (A)** 0.000560 (L)	**0.00089 (A)** 0.00083 (L)	0.00097 (A) **0.0011 (L)**	**0.00299 (A)** 0.00237(L)	0.0129	0.000296
EP	(Kg PO_4 eq)	**0.000144 (A)** 0.000143 (L)	**0.000192(A)** 0.000179(L)	0.000209 (A) **0.000228 (L)**	**0.000717 (A)** 0.000568 (L)	0.00313	0.000061

A = Abuja, L = Lagos. Box fill indicates ranking of impact: dark grey = highest impact, light grey = lowest impact; bold represents the city with the higher impact for each category.

2.3.4. Interpretation

The interpretation of the life cycle results includes identification of the main drivers of the impacts ('hot spots') in the life cycle, the consideration of the limitations of the study, and the sensitivity analysis. Three aspects were explored in the sensitivity analysis: (i) the effects of using the alternative LCIA method (ReCiPe 2016 Midpoint (H). V1.13); (ii) the assessment of the impact of reducing fugitive CH_4 emissions for the LFGTE system; and (iii) the assessment of the impact of increasing the conversion efficiency of the WtE systems.

3. Results

3.1. LCA Characterisation Results

The characterisation results for each impact category of the WtE systems for Abuja and Lagos are given in Table 5. Both cities exhibit very similar trends in the results obtained.

Table 5 and Figures 3 and 4 show that for both cities the DBGs had the highest impact in all categories except GWP and POCP, where LFGTE had by far the highest impact.

National grid electricity had the lowest impact in three out of six selected categories (GWP, AP, and EP), while AD had the lowest in ADP and HTP, with incineration having the lowest impact for POCP. Further analysis per impact category is given below (Figures 5–10).

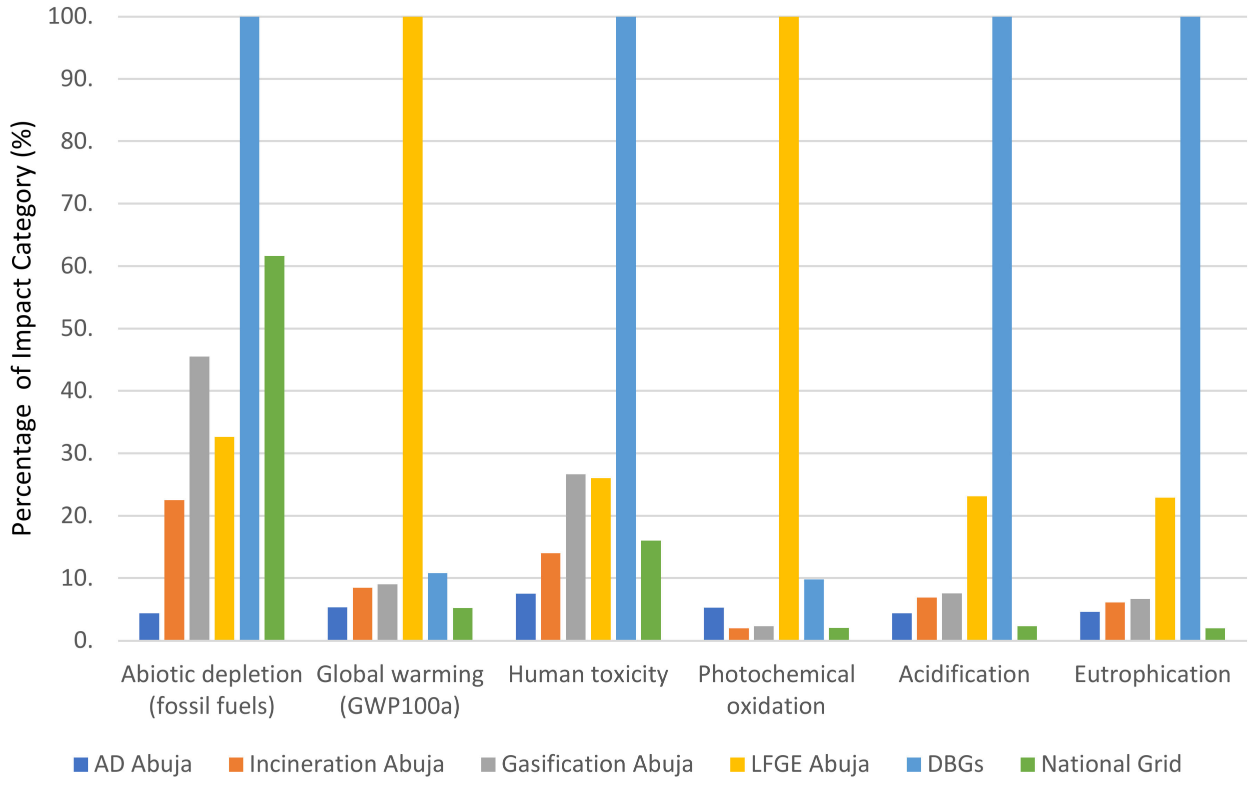

Figure 3. Abuja: LCA characterisation results for 1 kWh electricity output by WtE systems, DBGs, and national grid.

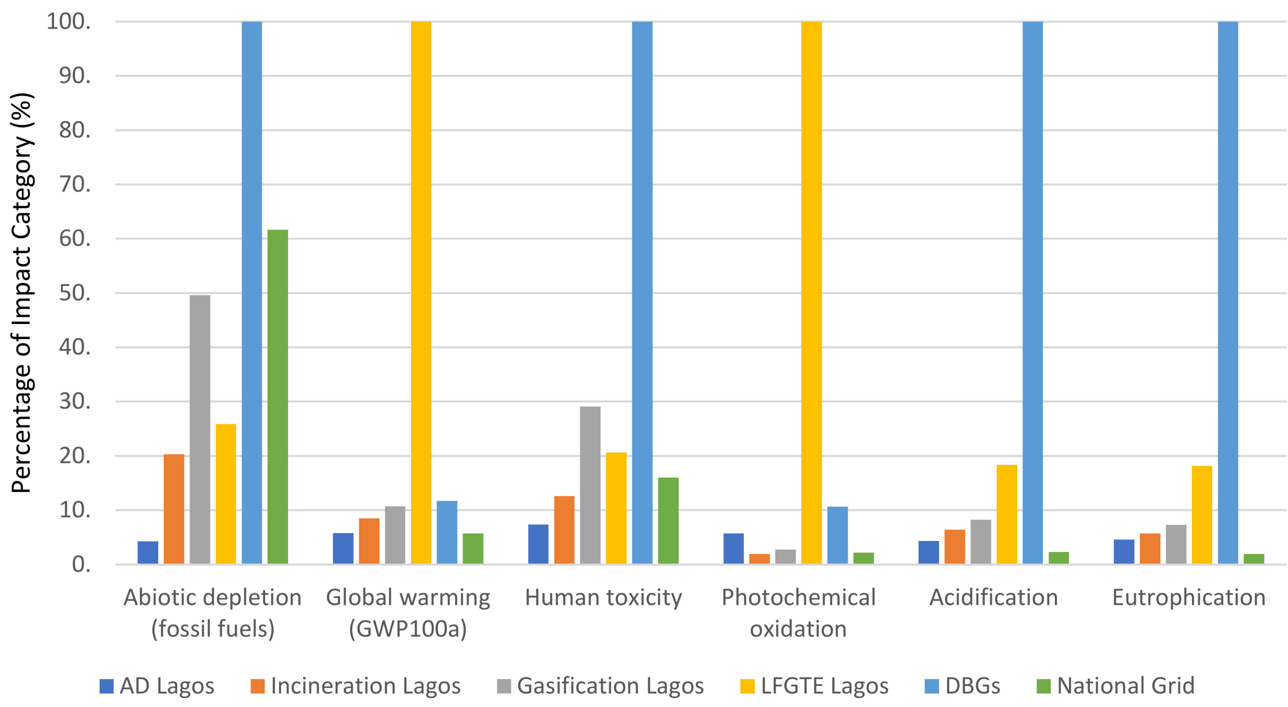

Figure 4. Lagos: LCA characterisation results for 1 kWh electricity output by WtE systems, DBG, and national grid.

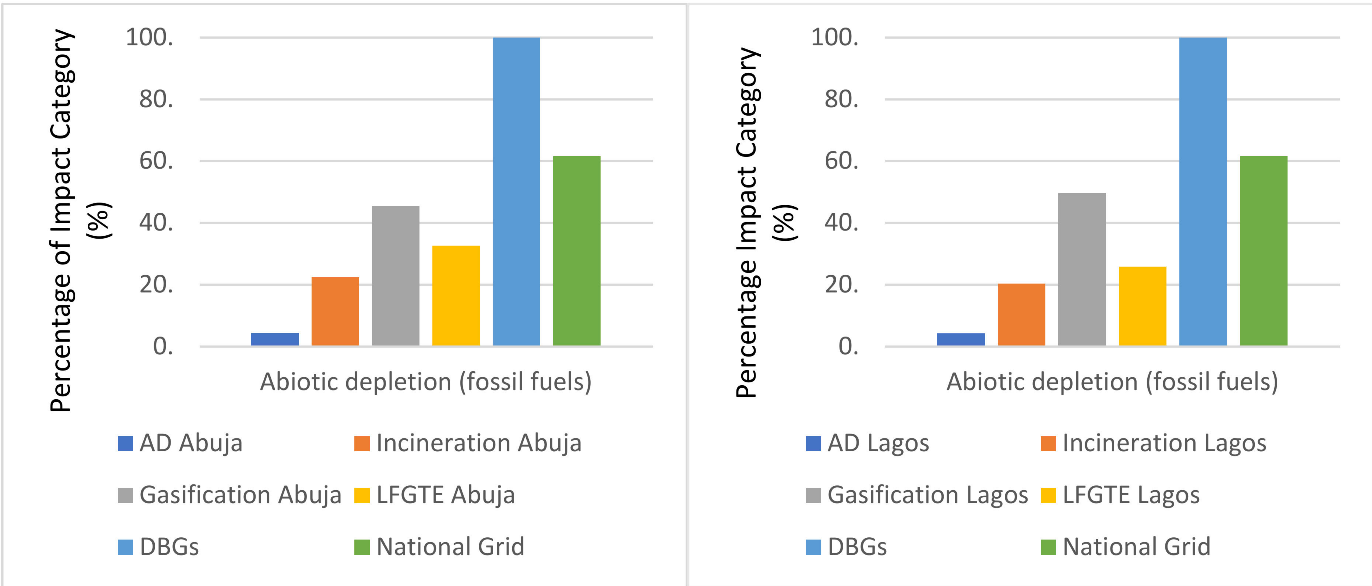

Figure 5. AD (fossil fuels) results for 1 kWh electricity output by WtE systems, DBGs, and national grid: Abuja (**left**) and Lagos (**right**).

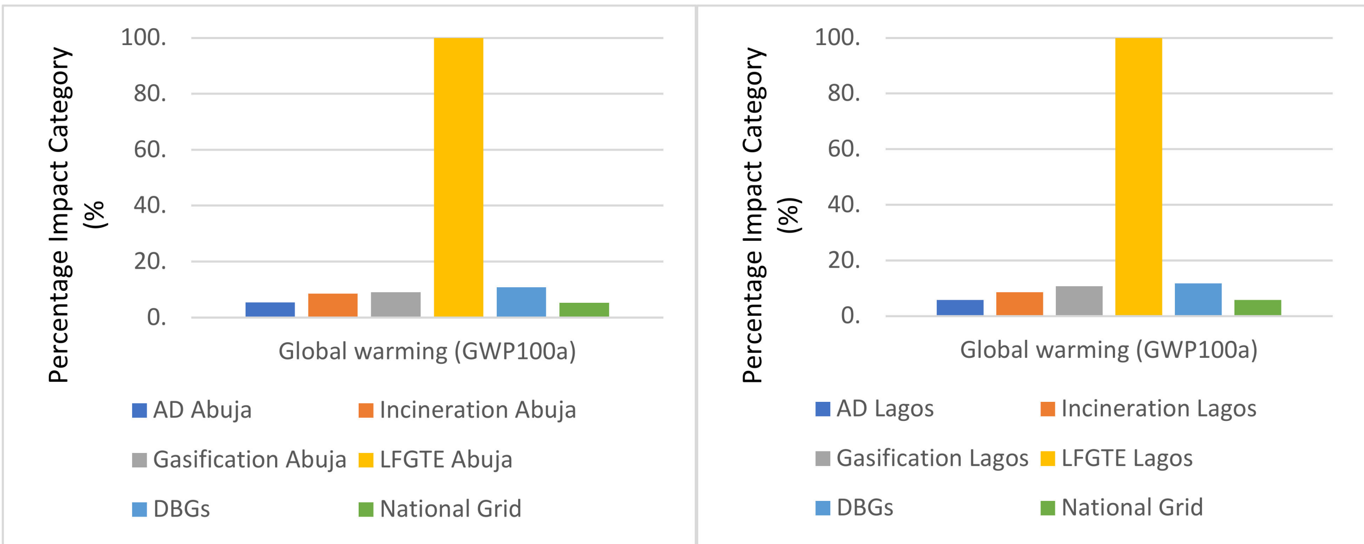

Figure 6. GWP results for 1 kWh electricity output by WtE systems, DBG, and national grid: Abuja and Lagos.

From Table 5 and Figure 5, DBGs had the highest impact on ADP (fossil fuels) (14 MJ), this being nearly double that of the next highest WtE electricity production system. The use of diesel fuel in DBGs contributed approximately 96% to this category, while grid electricity had the second highest impact in this category from the use of natural gas contributing approximately 99% to the score. AD on the other hand had the least impact (Abuja: 0.62 MJ, Lagos: 0.60 MJ), with diesel consumption for the MSW collection and transport being a main driver accounting for approximately 86% in this impact category (See Supplementary Materials, Tables S9 and S10). For ADP for the gasification system, the main driver was the consumption of grid electricity for the process operation. For incineration and LFGTE, their intermediate level of impact on ADP was driven mainly by diesel consumption for the MSW collection and transport (approximately 76% for both). In all scenarios, except for gasification and grid electricity, diesel consumption contributed the most to the ADP impact category.

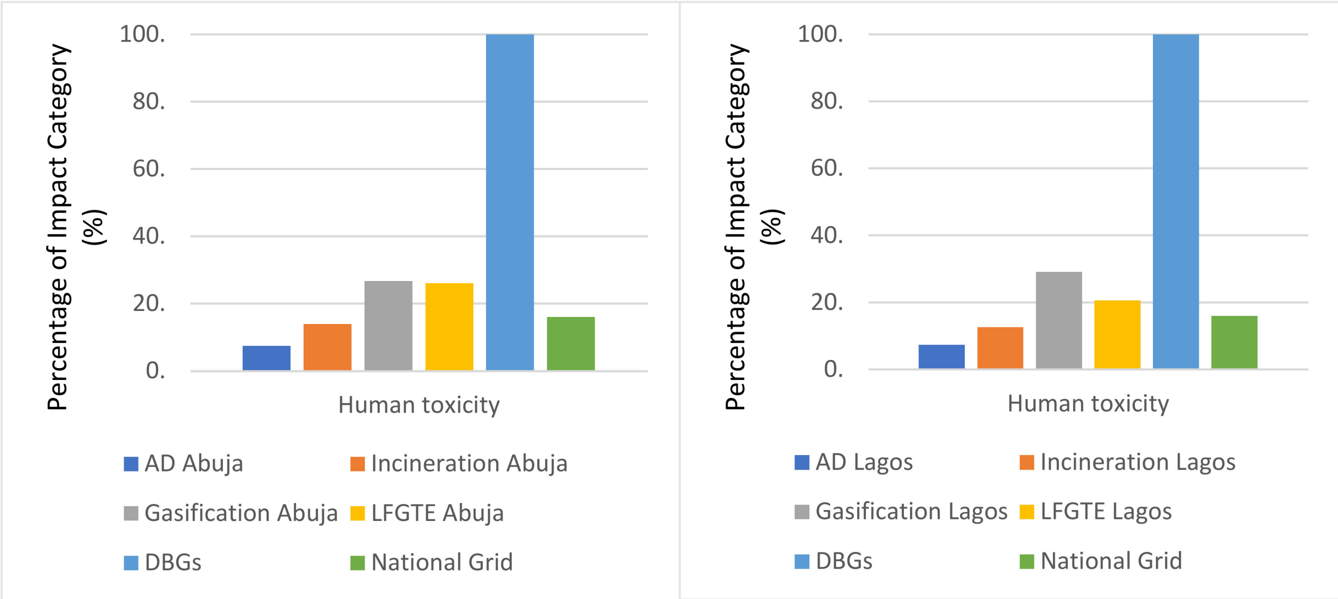

Figure 7. HTP results for 1 kWh electricity output by WtE systems, DBGs, and national grid: Abuja and Lagos.

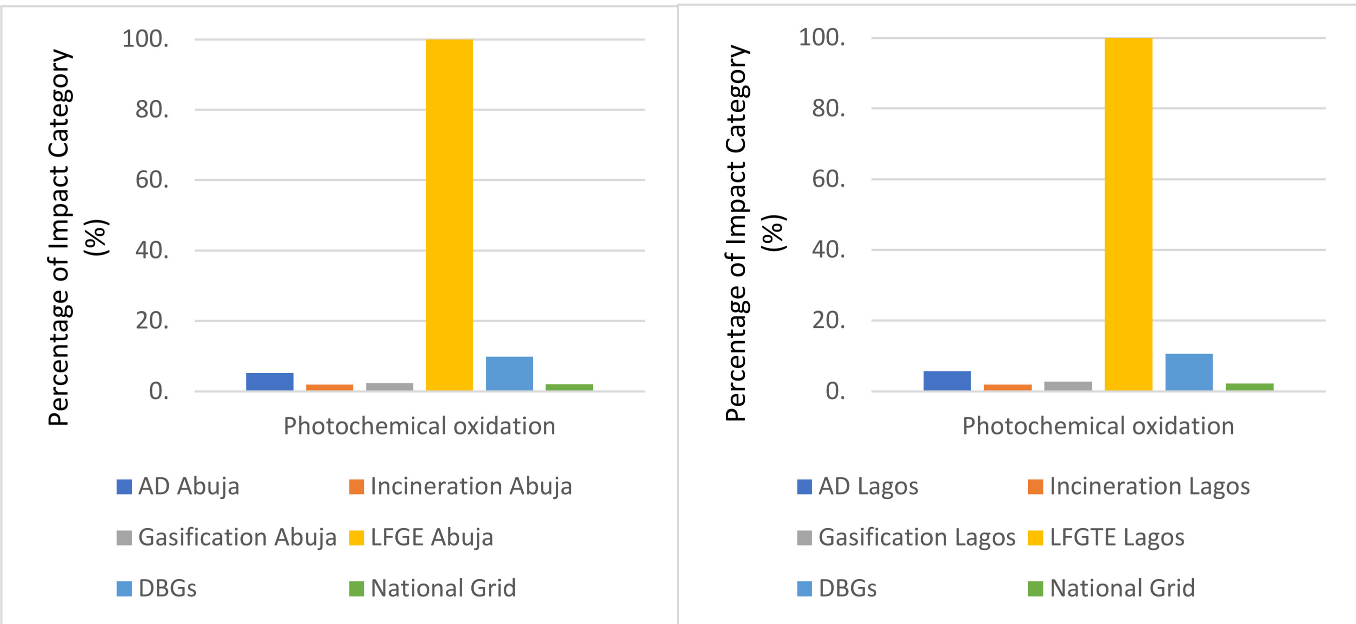

Figure 8. POCP results for 1 kWh electricity output by WtE systems, DBGs, and national grid: Abuja and Lagos.

For GWP, Figure 6 and Table 5 show clearly that LFGTE has the highest impact in this category amongst all the scenarios (Abuja 9.5 kg CO_2 eq/kWh, Lagos 8.7 kg CO_2 eq/kWh). The main driver for this impact was the emissions of 50% of the CH_4 produced in the landfill directly to the atmosphere as a 'fugitive' loss (the captured other 50% of the CH_4 produced is converted to CO_2 during combustion for electricity generation). As such, fugitive methane emissions contribute to approximately 95% of the GWP impact score for the electricity produced from LFGTE. The next (and much lower) highest score for GWP impact was from the electricity from the DBGs, where CO_2 during the combustion of fossil diesel accounted for 99% of the GWP score. Grid electricity had the least impact in this category, with a GWP of 0.497 kg CO_2 eq/kWh from its natural gas consumption.

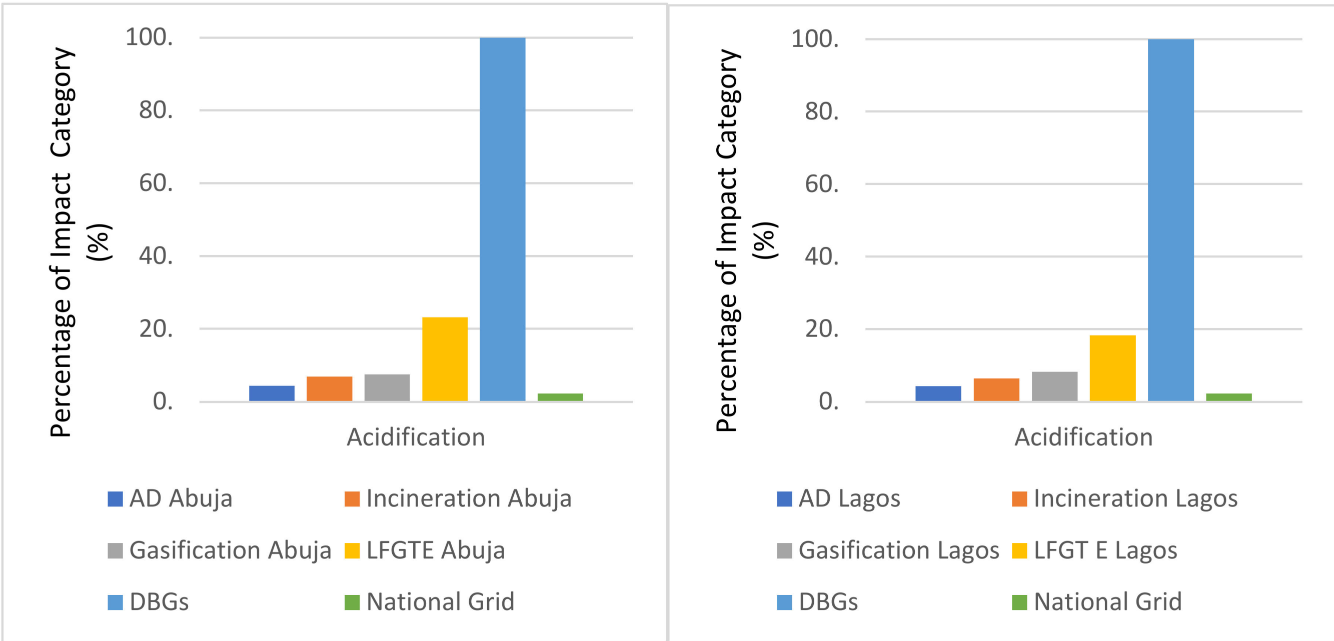

Figure 9. AP results for 1 kWh electricity output by WtE systems, DBG, and national grid: Abuja and Lagos.

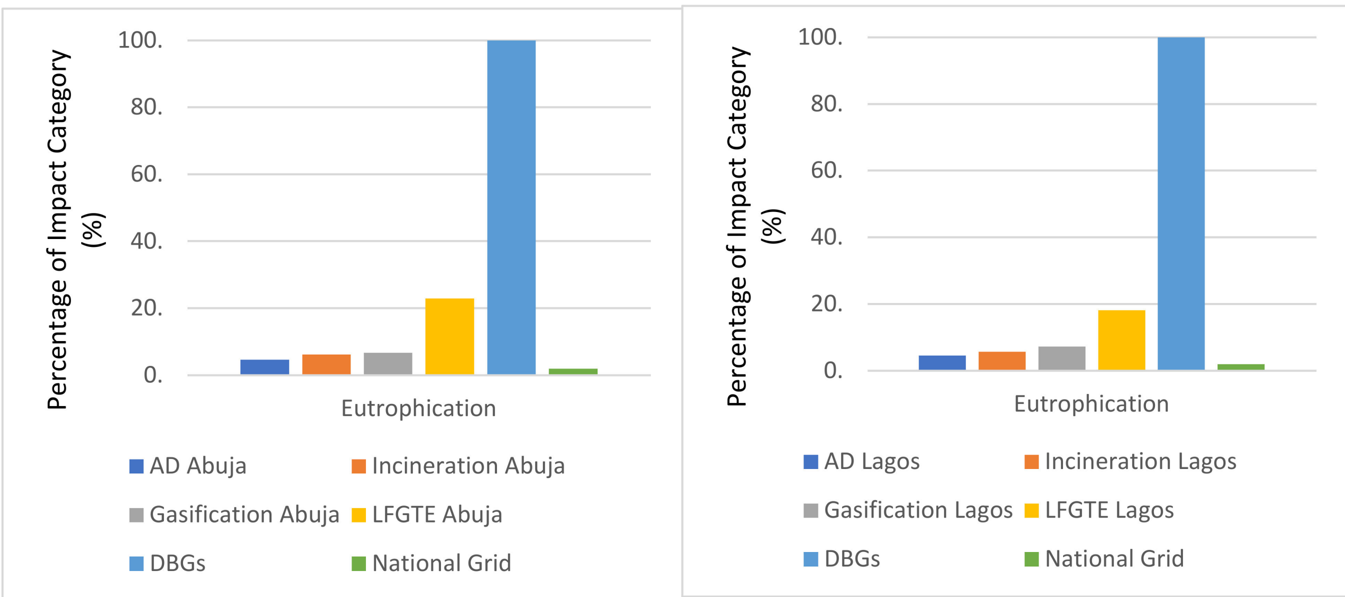

Figure 10. EP results for 1 kWh electricity output by WtE systems, DBGs, and national grid: Abuja and Lagos.

In the case of the HTP, the fate, exposure, and effects of toxic substances such as PM, SO_x, NO_x, and heavy metals are the main drivers in this impact category [64]. The results in Table 5 and Figure 7 show that electricity from the DBGs (0.0732 kg 1.4 DB eq/kWh) was the worst alternative, with NO_x emissions contributing approximately 39% to this impact category. Gasification (Abuja: 0.0195 kg 1.4 DB eq/kWh, Lagos: 0.0213 kg 1.4 DB eq/kWh) ranked second in this category due to Ni, Cd, and NO_x emissions, which accounted for approximately 34, 14, and 9%, respectively, of the contributions to this impact category. These emissions came from the diesel consumption from waste collection and transportation (approximately 37%) and the gasification process itself (approximately 33%). Grid electricity, LFGTE, and incineration (due to assumed good combustion control) had rankings of third, fourth, and fifth, respectively, in this category. AD was ranked sixth, having the lowest HTP of 0.0055 kg 1.4 DB eq/kWh and 0.0054 kg 1.4 DB eq/kWh for both Abuja and Lagos, as shown in Figure 7.

POCP represents the formation of reactive agents hazardous to human health and the ecosystem (Figure 8). Here, CH_4, VOCs, and CO are significant for POCP [65]. The system with by far the highest POCP score was the LFGTE scenario (Abuja 0.00202 kg C_2H_4 eq/kWh, Lagos 0.00186 kg C_2H_4 eq/kWh) due to the high levels of fugitive emissions of CH_4 (approx. 96% of the impact scores) from the landfill gas produced. This is followed, at a much lower level, by the electricity from the DBGs with a POCP of 0.000198 kg C_2H_4 eq/kWh, due mainly to CO emissions (contributing approximately 74% to the impact category). For AD, the POCP score was also largely due to the fugitive emissions of CH_4, albeit in a very much smaller quantity compared with that in the LFGTE scenario. This was followed by gasification and grid electricity, with ethane being the main contributor to its POCP. Incineration (Abuja 0.0000396 kg C_2H_4 eq/kWh, Lagos 0.0000357 kg C_2H_4 eq/kWh) had the lowest score in this impact category. For all the WtE systems, some small CO contribution to their POCP scores occurred from the diesel consumed during the waste collection and transportation.

For the AP impact category, the main pollutants are SO_x, NO_x, NH_3, and HCI emissions [53]. Table 5 and Figure 9 show that the DBGs (0.0129 kg SO_2 eq/kWh) have the highest impact by far due to combustion of the diesel and its associated NO_x emissions accounting for approximately 91% of the impact score. This is followed by LFGTE, gasification, incineration, and AD. Grid electricity (0.000296 kg SO_2 eq/kWh) has the least impact in this category.

The EP category is driven by high levels of plant macronutrients comprising nitrogen and phosphorus entering the environment. Nitrogen (N), Nitrate (NO_3^-), NO_x, PO_4, and chemical oxygen demand (COD) are significant contributors to EP. The electricity from the DBGs with an EP of 0.00313 kg PO_4 eq/kWh had the highest impact in this category, as indicated in Table 5 and Figure 10. This was based on the high concentration of NO_x (also a driver for AP), which accounted for approx. 98% of the contribution to EP. This was followed by much lower scores for LFGTE (Abuja 0.000717 kg PO_4 eq/kWh, Lagos 0.000568 kg PO_4 eq/kWh) (NO_x accounting for approx. 97%). Grid electricity (0.000061 kg PO_4 eq/kWh) had the lowest EP score overall with gasification, incineration, and AD ranked third, fourth, and fifth, respectively.

Overall, for both Abuja and Lagos, electricity production from the DBGs was the scenario with generally the highest impact scores in most categories, while grid electricity was the best scenario from an environmental perspective. When considering just the four WtE systems, AD had the least impact in all the impact categories except POCP, while LFGTE had the highest impact in five out of the six impact categories for both cities.

The results also indicate that Abuja had slightly higher impact scores in all the selected categories for the WtE systems except for gasification, but the relative ranking between the WtE systems was consistent in both cities (AD best, LFGTE worst).

3.2. Sensitivity Analysis

There were three sensitivity analyses conducted in this study. The first involved investigating whether the findings were sensitive to the choice of LCIA method. This was tested by comparing the LCIA results obtained from the CML method with those from the ReCiPe 2016 Midpoint (H) v1.13 method. The second sensitivity analysis focused on the effect of assuming 30% fugitive methane emissions on the environmental impacts of LFGTE, while the third sensitivity analysis was centred on the effect of a 10% increase in the conversion efficiency on the environmental impacts of the WtE systems. Figures 11–14 give the results for the first sensitivity analysis of the environmental impacts involved using different impact assessment methods.

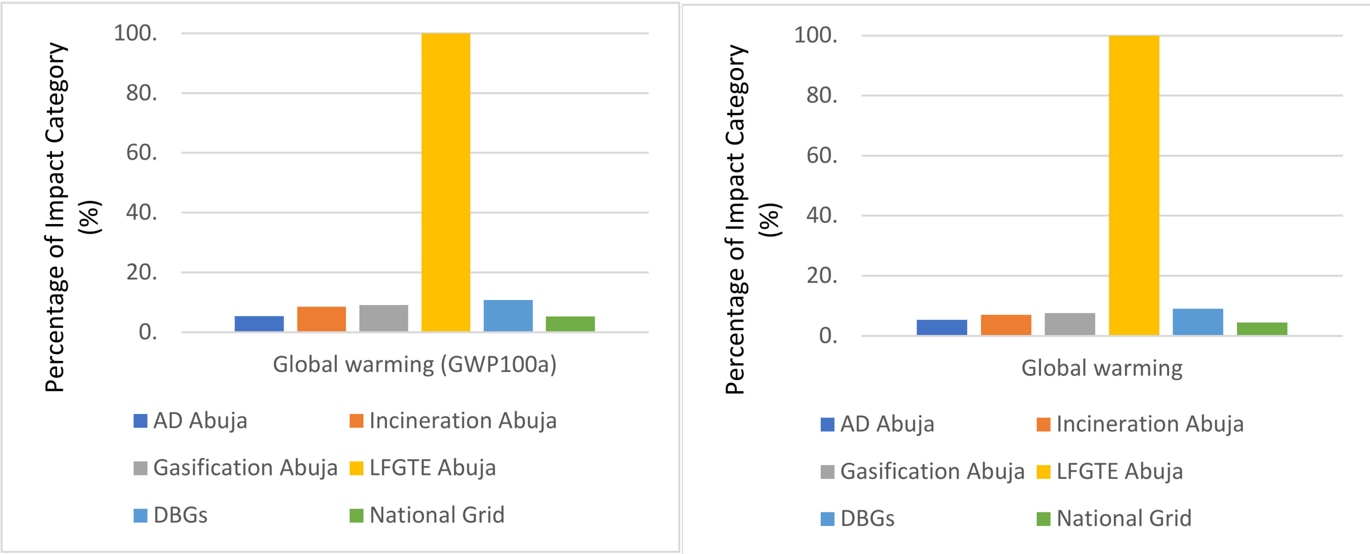

Figure 11. Sensitivity analysis: comparison of global warming characterisation results of the WtE systems, DBGs, and grid electricity using CML and ReCiPe impact assessment methods for Abuja.

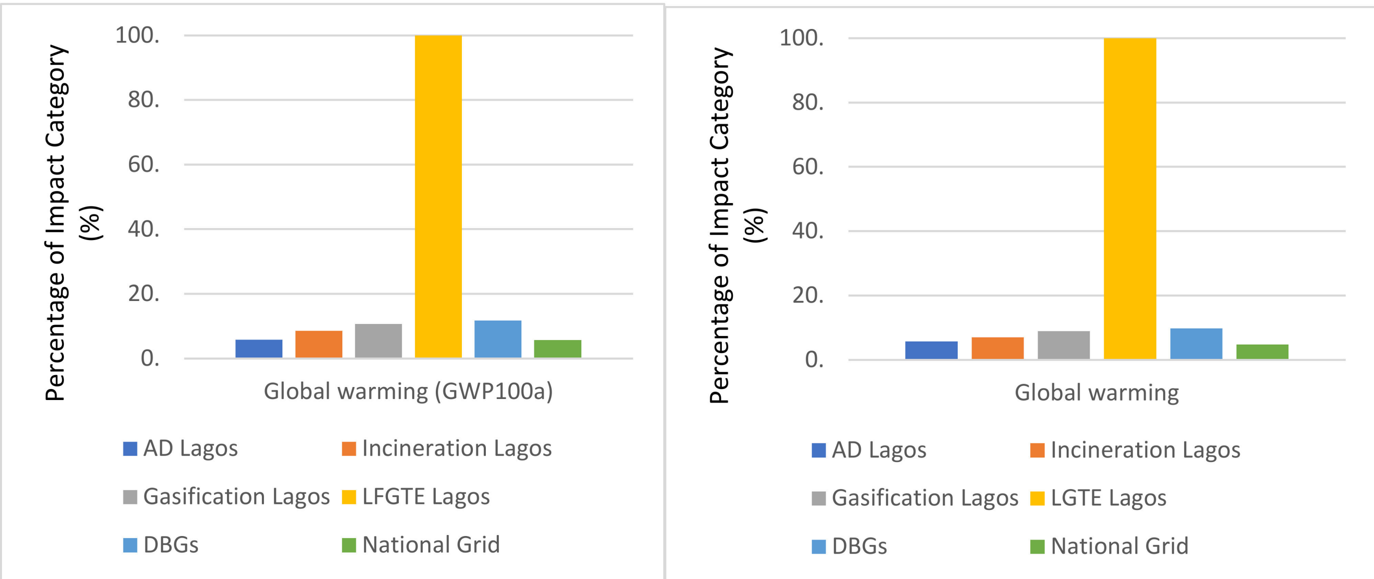

Figure 12. Sensitivity analysis: comparison of global warming characterisation results of the WtE systems, DBGs, and grid electricity using the CML and ReCiPe impact assessment methods for Lagos.

As shown in Figures 11–14, the use of an alternative impact assessment method led to no differences in the ranking order, or the general relative scale of the systems investigated in these impact categories. AD and grid electricity still clearly had the lowest impact and the DBGs the highest impact for the categories considered (GWP and AP). It was concluded that the LCIA results were not sensitive to the choice of an alternative LCIA method.

With regard to the second sensitivity analysis, Table 6 shows the results when the fugitive methane emissions to the environment were reduced from the base case of 50% fugitive emissions to 30% fugitive emissions for LFGTE.

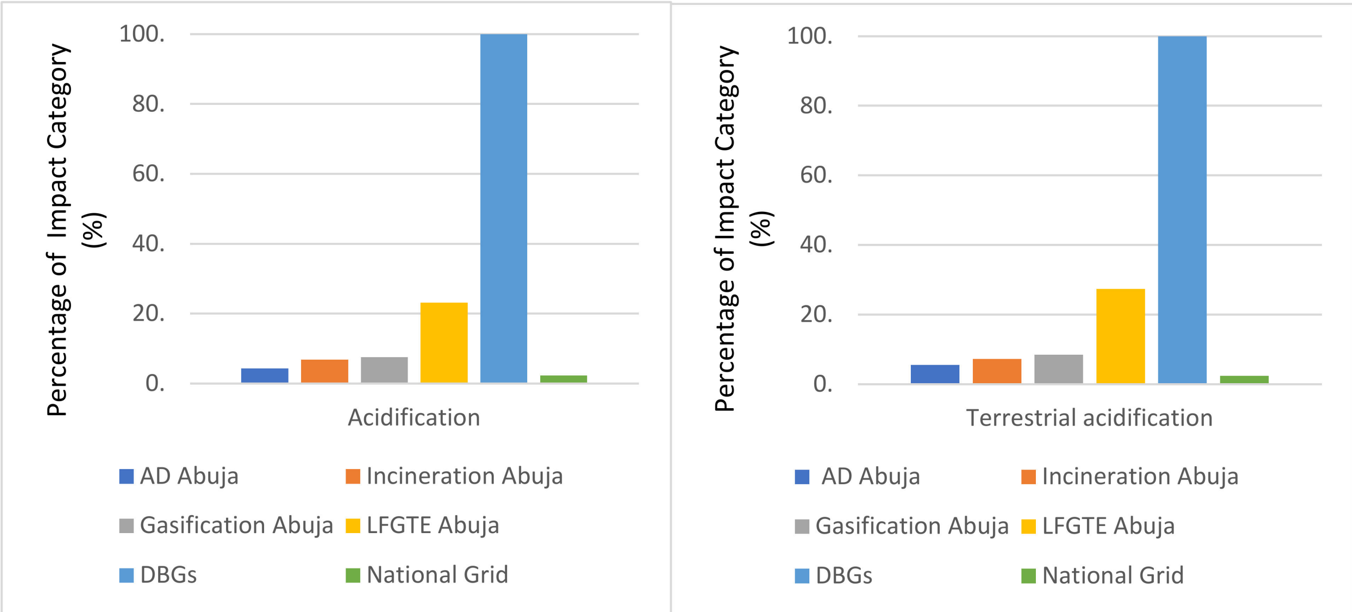

Figure 13. Sensitivity analysis: comparison of acidification characterisation results of the WtE systems, DBGs, and grid electricity using CML and ReCiPe impact assessment methods for Abuja.

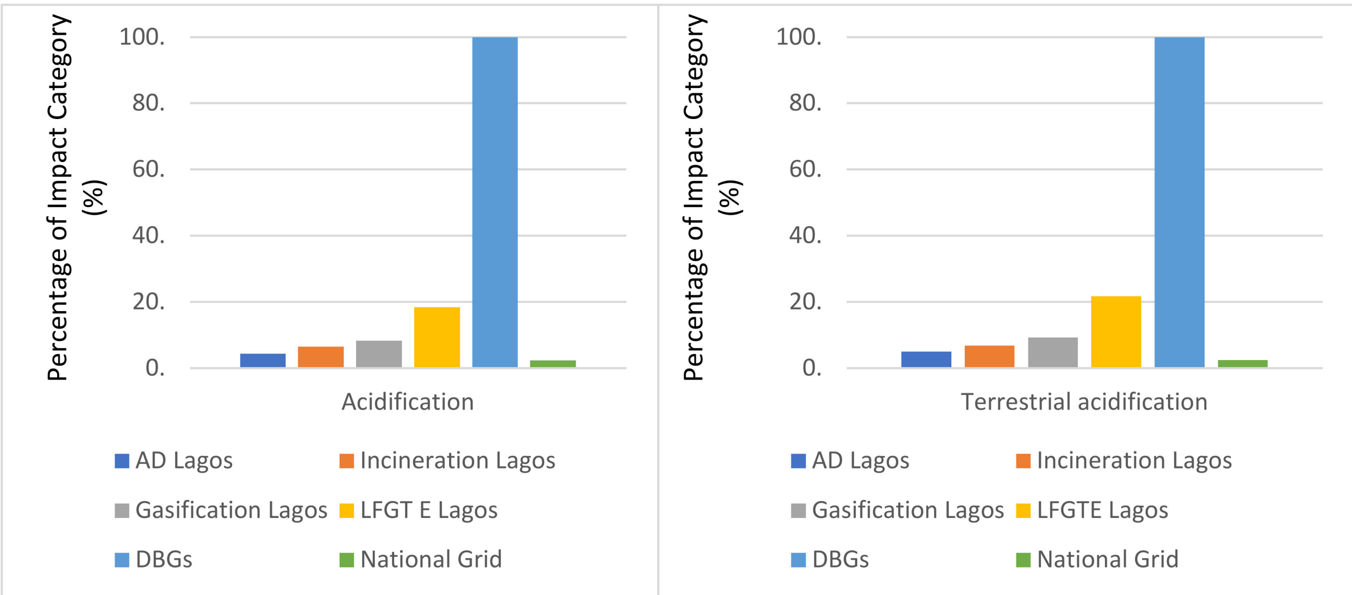

Figure 14. Sensitivity analysis: comparison of acidification characterisation results of the WtE systems, DBGs, and grid electricity using CML impact assessment and ReCiPe impact assessment methods for Lagos.

Table 6. Sensitivity analysis: emissions in GWP and POCP per kWh electricity produced with alternative assumptions for fugitive CH_4 emissions.

Impact Category	Unit	LFGTE, 50% CH_4 Fugitive Emission	LFGTE, 30% CH_4 Fugitive Emission
GWP	(Kg CO_2 eq)	9.5 (A) 8.7 (L)	4.6 (A) 4.1 (L)
POCP	(Kg C_2H_4 eq)	0.00202 (A) 0.00186 (L)	0.00093 (A) 0.00087 (L)

Here, the sensitivity results indicated that reducing the fugitive CH_4 emissions to 30% implies that more landfill gas is captured, resulting in an increase in the electricity-generating potential of LFGTE. These two factors reduced the environmental impacts of LFGTE, especially considering that fugitive methane was a key contributor to these impact categories. The electricity generated for Abuja and Lagos increased from 135 to 189 and from 171 to 221 kWh/t, respectively, with this reduction in fugitive methane emissions to 30% (by more efficient landfill gas capture). This improvement gave an almost 50% reduction in GWP (Abuja from 9.5 to 4.6 kg CO_2 eq/kWh, Lagos from 8.7 kg to 4.12 kg CO_2 eq/kWh). For POCP, a similar (approx. 50%) reduction was observed from 0.00202 kg to 0.00093 kg C_2H_4 eq kWh/t for Abuja and 0.00186 kg to 0.000873 kg C_2H_4 eq/kWh for Lagos. However, these results did not change the relative ranking of LFGTE when compared with the other WtE systems or the DBGs and grid electricity. LFGTE still had the lowest electricity-generating potential amongst the WtE systems and the highest GWP and POCP overall.

With regard to the third sensitivity analysis, Table 7 shows the characterisation results when the conversion efficiency is increased by 10% for the WtE systems.

Table 7. Sensitivity analysis: effect of an assumed 10% variation in the conversion efficiency on life characterisation results for the WtE systems.

Impact Category	Unit	AD	Incineration	Gasification	LFGTE	DBGs	Grid Electricity
ADP (Fossil Fuels)	(MJ)	**0.562 (A)** 0.548 (L)	**2.88 (A)** 2.60 (L)	5.81 (A) **6.35 (L)**	**4.17 (A)** 3.58 (L)	14.1	8.67
GWP	(Kg CO_2 eq)	**0.461 (A)** 0.460 (L)	**0.73 (A)** 0.68 (L)	0.78 (A) **0.85 (L)**	**8.63 (A)** 8.60 (L)	1.02	0.497
HTP	(Kg 1.4 DB eq)	**0.00498 (A)** 0.00489 (L)	**0.0093 (A)** 0.0084 (L)	0.018 (A) **0.019 (L)**	**0.0173 (A)** 0.0148 (L)	0.0732	0.0117
PCOP	(Kg C_2H_4 eq)	0.000096 (A) 0.000096 (L)	**0.000036 (A)** 0.000033 (L)	0.000042 (A) **0.000046 (L)**	**0.00184 (A)** 0.00095(L)	0.000198	0.0000406
AP	(Kg SO_2 eq)	**0.000512 (A)** 0.000510 (L)	**0.00081 (A)** 0.00075 (L)	0.00089 (A) **0.00097 (L)**	**0.00272 (A)** 0.00233 (L)	0.0129	0.000296
EP	(Kg PO_4 eq)	**0.000131 (A)** 0.000130 (L)	**0.00019 (A)** 0.00016 (L)	0.00019 (A) **0.00021 (L)**	**0.000652 (A)** 0.000559 (L)	0.00313	0.000061

A = Abuja, L = Lagos; Box fill indicates the rankings of impact: dark grey = highest impact, light grey = lowest impact; bold represents the city with the higher impact for each category.

In this case, the sensitivity results revealed that increasing the conversion efficiency would result in an increase in the electricity-generating potential of the WtE systems. This reduces the environmental impacts of the WtE systems for all the impact categories considered. For instance, the electricity generated from AD increased from 667 to 734 and from 683 to 751 kWh/t for Abuja and Lagos, respectively (see Supplementary Table S11). In terms of environmental impacts, an approx. 9% reduction was seen in most of the impact categories for both cities for all the other WtE systems. Furthermore, this also changed the relative ranking of the WtE systems slightly, compared with the DBGs and grid electricity, particularly for AD, which now had the least impact in terms of GWP of all the systems investigated and was now 'better' than grid electricity (0.497 kg CO_2/kWh), which previously had the least in this category. LFGTE still had the lowest electricity-generating potential amongst the WtE systems and the highest GWP overall. It was concluded that a 10% improvement in the efficiency of the conversion of MSW feedstock into electricity in the WtE systems can influence the relative rankings of at least one of the WtE systems (AD) relative to the grid electricity.

4. Discussion

This paper has presented an LCA-based assessment of the environmental impacts potentially arising from the adoption of WtE systems in Lagos and Abuja, Nigeria. This was also compared with the use of grid electricity and DBGs. The ranking of the WtE systems with each other clearly indicated LFGTE as having the highest impact on GWP, POCP, AP, and EP. This is similar to the findings from other studies in different countries.

For instance, Gunamantha [66], in a study involving the LCA of five MSW-to-energy options in Yogyakarta, Indonesia, showed LFGTE as the worst option with respect to these four impact categories. Zaman [63] indicated in an LCA study conducted in Sweden that LFGTE had a GWP of 3.44 kg CO_2 eq per kWh and a POCP of 0.000538 kg C_2H_4 per kWh, making it the highest in those categories compared with the other WtE technologies, such as incineration and gasification. These values are lower compared with those obtained in the present study with 50% CH_4 fugitive emissions, possibly due to differences in the waste composition and climate conditions of the two study areas, but with similarities to those obtained at 30% CH_4 fugitive emissions. Given this, LFGTE has been confirmed in this present study and several other studies [67–70] as a relatively low-energy-yielding, high-environmental-impact approach for WtE, although some energy can be recovered.

Our study was able to identify for both Lagos and Abuja that AD was the only WtE scenario having the least environmental impact for all the impact categories except for POCP. It is therefore the preferred WtE option in terms of the overall environmental 'profile', considering that both cities have a high amount of organic waste in their respective MSW streams (Abuja 47% and Lagos 46% by mass of MSW).

This finding is consistent with that of Chaya and Gheewala [71], where it was concluded that the environmental impacts and energy balance of AD was preferable to incineration in Thailand.

More than 60% of the waste in this study was biodegradable and thus suitable for AD, with the wet nature of the waste making direct combustion difficult. However, regarding AD, the findings in the present study contrast to a degree with those of Gunamantha [66], who explored five MSW-to-energy options in Yogyakarta, Indonesia, and concluded that gasification was the best option with regard to environmental impacts. This was attributed to gasification performing best in the impact categories of global warming, eutrophication, photochemical oxidant formation, and acidification. In our case, gasification was broadly similar to incineration but much less than AD. In the case of incineration having the least POCP, this was consistent with the findings of Adeleke et al. [1], who concluded that this was due to the low emissions of CH_4, and was considered a future alternative that could permit the phasing out of landfilling in South Africa, while Rajcoomar and Ramjeawon [72] also concluded that incineration had the least POCP of the alternatives due to the low concentration of volatile organic compound emissions in their LCA study of MSW management scenarios for Mauritius.

The comparison of these WtE systems with DBGs shows their clear superiority, in environmental impact terms, over such backup generator systems. In contrast, grid electricity had the least impact in three out of the six impact categories. This emphasises the need to substitute for electricity from DBGs by supplementing the capacity and reliability of the national grid. In this regard, AD is a WtE system that could achieve these two objectives. This comes from AD being environmentally the best out of the WtE technologies examined and having the highest electricity-generating potential in kWh/t. Similar findings from LCA research have been outlined by Schofield [73], involving the comparison of the environmental impacts of diesel-generated electricity with hybrid diesel–wind electricity for off-grid first nation communities in Ontario, Canada. Here, it was concluded that a proposed 250 KW wind turbine could reduce the environmental impacts associated with the current diesel energy systems by 12–46%, depending on the wind energy potential.

Likewise, Somorin et al. [74], who conducted an LCA of self-generated electricity (SGE) in Nigeria, and Jatropha biodiesel as an alternative power, showed that SGE from 5 kVA diesel generators contributes 1625 kg CO_2 eq/MWh of greenhouse gas (GHG) emissions, which, along with other environmental burdens, can contribute 389 million tonnes of CO_2 eq to climate change every year. However, a diesel fuel displacement with Jatropha biodiesel can reduce annual GHG emissions from SGE by 76%, provided combined cycle power plants are adopted for the embedded power generation. Aslam et al. [75] gave a similar illustration when assessing the energy potential of waste biomass in producing renewable electrical energy for small-scale electricity generation in Tanzania. Here, energy generated from waste biomass residues using AD and/or gasification could potentially substitute for diesel fuel used in small-scale dual-fuel diesel generator sets and thus provide more affordable electricity whilst reducing dependency on fossil fuels.

For the sensitivity analysis, the key finding that the results in this present study were not sensitive to the used impact methods was similar to that of other studies such as [76], in which a comparative LCA of MSW management systems in Kırklareli, Turkey, was performed.

The increase in the conversion efficiency resulting in lower environmental impacts for the WtE systems could be related to the findings of [77], who noted that increasing parameters such as recycling rates or conversion efficiencies resulted in lower environmental impacts during the LCA of MSWM strategies in the Tricity region of India. Moreover, a lower fugitive CH_4 emissions of 30% from an LFGTE system, giving it a considerably improved performance, was consistent with the findings of an LCA of potential MSW management scenarios in Tanzania, conducted by [78]. However, the lower emissions were not sufficient to change the ranking of LFGTE as it remained the worst WtE system. This proved to be important because reaching even lower fugitive CH_4 emissions in an unmanaged landfill in Nigeria looks highly ambitious and unrealistic. This means that landfill remains a poor option, at least in environmental impact and quantum of electricity generated terms. This may not apply from both an economic and social perspective as LFGTE could prove to be a cheaper option compared to other WtE systems and with less negative social impacts. This can only be ascertained further by performing an LCC, sLCA, or LCSA to assess the overall sustainability of LFGTE.

As noted previously, this present study is prospective rather than retrospective, with several uncertainties that inevitably apply to perceptions concerning a future condition. For instance, the maturity of technology is an important point that needs to be considered when comparing different technologies. Nevertheless, this study showed the environmental burdens and benefits based on the various developmental levels of the technologies, as represented in the reasonably recent literature and databases (mainly in the last 5 to 10 years). Moreover, this study had certain limitations regarding data acquisition and data availability, as is common with many comparative LCA studies. The data utilised in the study, such as the emissions data and default values of specific parameters, involved a combination of different databases and relevant literature sources representing the study locations.

This study investigated the WtE technologies as 'standalone' scenarios for the purpose of clarity and as appropriate to the prospective and relatively 'high level' analysis conducted in the absence of site-specific, highly granular data. Regardless, the analysis is considered suitably robust to highlight the strengths and weaknesses of each WtE scenario (and its comparators of DBGs and grid electricity) and thus to provide valuable insights for the future and a more detailed analysis. This could explore the environmental benefits of the hybrid and/or optimised applications of these systems, which see the weakness of one being complemented by the strength of the others to enhance the utilization of WtE, as indicated by [36]. For instance, the environmental benefits and the electricity-generating potential of a hybrid system of AD and incineration could serve as a basis for future exploration, considering that these were the two WtE systems with the best environmental profiles.

As a nation, Nigeria has struggled to meet the electricity demand of its populace due to limited technologies and its inability to diversify into multiple sources of electrical power generation [79]. For Abuja and Lagos, this study has shown that employing the concept of WtE has considerable potential for improving electricity supply and distribution in a sustainable way. For households, the harnessing of energy from MSW will not only improve the basic electricity supply for their residents but could also provide access to electricity supply to the several remote areas. The same applies for businesses, where the atmosphere of profitable business enterprise operations is unsustainable for many local industries due to their dependence on private generators for power supply.

Moreover, the Federal Capital Territory within which Abuja is located has a considerable number of relatively remote villages that have little or no access to electricity. This makes them prime candidates for the possible adoption of WtE from the perspective of either extending the current grid electricity, possibly substituting for DBGs, or adding to the existing grid supply via some local grid supply fed by WtE systems. According to Suberu et al. [80], an estimated power generation potential of 442 megawatts (MW) from MSW using different WtE systems could improve the power supply in the city of Lagos by adding to the power supply which was reduced from the initial 800 MW to 300 MW and has not increased since 2011. In the present study, it was found that regardless of the differences between both cities, AD emerged as a viable option amongst the other WtE systems. This is likely due to the MSW composition in both cities having a high amount of food waste [81]. Thus, the potential amount of electricity that could be generated from the best WtE system (AD) (see Supplementary Material Table S12) could increase the electricity supplies to Abuja and Lagos by approximately 5% and 19%, respectively. This new supply would collectively increase the 4000 MW of the country's grid average national electricity generation [49] by approximately 23% (Table 8).

Table 8. Total electricity supply from the national grid and AD for Abuja, Lagos, and Nigeria.

	Grid Electricity Supply (MW)	Additional Electricity Supply from AD (MW)	Total Electricity Supply (MW)
Abuja	229 [49]	12	241
Lagos	300 [49]	58	358
Nigeria	4000 [49]	932	4932

The adoption of WtE would not only improve electricity supply through the provision of alternative and clean energy (much better than DBGs and, in the best cases, relatively comparable in environmental impact per kWh to the national grid average generation), but it will also improve the current waste management system by addressing its environmental disposal needs. Thus, the implementation of an integrated solid waste management system that covers all levels from waste generation to the final disposal, including the energy recovery processes, aimed at solving the waste management problems, is something that needs to be considered by decision makers. For instance, value extraction from waste through material recycling can be carried out first before using the 'remaining' waste as 'feedstock' for WtE systems. This will no doubt result in less environmental impact, as indicated by previous studies such as [4,82], where it was confirmed that integrated waste management that included a material recovery facility (MRF), incineration with energy recovery, and landfilling processes would cause fewer environmental impacts than standalone processes. Thus, WtE systems are essential to solving the waste disposal problems as well as reducing the GHG emissions generated by MSW management whilst also generating renewable energy, all of which are key values within the circular economy concept [83]. However, there could be some issues with WtE systems. For example, there are the residues which remain after incineration that need to be considered. Apart from the ash being used as construction materials, there have been recent attempts at finding ways that the residues of incineration can be used to backfill underground excavations, such as abandoned mines, with a self-solidifying mixture prepared using technologies such as the hydraulic backfill technique (HBT) and the dry waste technique (DWT) [84].

In addition, a key finding in this study is that the results of the LCA carried out for the two cities were similar. The implication of this is that the differences that exist between the two cities in terms of geographical location and socio-economic status had little or no substantial effect on the environmental impacts that could possibly emanate from adopting WtE in both cities. This similarity could be attributed to several reasons but is primarily due to their similar waste compositions, similar demands for waste collection and transportation, and the assumed use of average grid electricity for any processed electricity needs. Given this, it is possible to expect similar findings for other cities of the country given that local differences may not exert much influence on the WtE scenario outcomes for environmental impacts. This echoes the findings of Rana et al. [77] when conducting the LCA of MSWM strategies in the Tricity region of India, which concluded that of all the scenarios considering the combination of recycling, composting, and sanitary landfill showed the least environmental impacts for the three different cities in India.

Regarding policies, the addition of electricity from WtE systems (in this case AD) to the current grid electricity is in line with the main goal of the National Energy Policy (NEP), which is aimed at creating energy security through a robust energy-supply mix by diversifying the energy supply and the energy carriers [85]. However, decision making on the selection of appropriate technologies is often challenging without performing an environmental impact analysis of the different proposed scenarios. Furthermore, the development of wrong policies based on non-optimal methods can create significant problems. Because of this, LCA assessment is a useful tool in determining the environmental impacts of the selected or proposed WtE systems [86].

Finally, the optimization of the three pillars of sustainability for waste management/WtE is a complex balance and is something that this present research has considered as part of its future contribution. Thus, there is a need to have as comprehensive an outlook as possible in terms of the economic evaluation of the cost and benefits of each proposed scenario using LCC alongside a social assessment via the sLCA. Nubi et al. [87], have performed and reported a complementary sLCA for WtE in Nigeria using the two cities in the present research. Thus, these two elements—LCA and sLCA for WtE systems in Nigeria have been implemented to date and can form valuable parts of the evolution of a more comprehensive LCSA to help the Nigerian government devise appropriate policies for sustainable waste management and electricity supply.

5. Conclusions

The following conclusions about the relative environmental impacts of potential WtE scenarios for Lagos and Abuja in Nigeria are drawn from this research:

- AD offers the highest electricity potential and is the most environmentally sustainable WtE option for Lagos and Abuja.
- The adoption of AD is expected to achieve the lowest environmental impact in Lagos and Abuja when compared only with the other WtE options.
- From the overall comparison of WtE technologies with the electricity from diesel backup generators and grid electricity in the two cities, DBGs had the highest or second highest environmental impacts in every category; LFGTE had much higher GWP and POCP scores due to fugitive methane emissions. In contrast, grid electricity had the least impact on GWP, AP and EP, POCP, and AP, with AD having the least impact on abiotic depletion and HTP.
- The adoption of WtE in this case could potentially supplement the current grid electricity and substitute for the use of diesel backup generators.
- From the sensitivity analyses performed, it was clear that the results were reliable and that changes in emissions, particularly for LFGTE, did not change the ranking even though there was a reduction of approximately 50% in GWP and POCP.
- There was a consistency in the WtE LCA findings between Lagos and Abuja despite their somewhat different contexts; this was largely due to the similarities in waste composition and hence the modelled performance of the WtE systems between the two cities.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14159252/s1, Sections S1–S7 [61,62,88–93].

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