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Application of Multi-Criteria Decision-Making Process to Select Waste-to-Energy Technology in Developing Countries: The Case of Ghana

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Abstract: Municipal solid waste (MSW) in the Accra region of Ghana has created the need for innovative ways to deal with waste management crises facing the city. The goal of this study is to use the analytical hierarchy process (AHP) to select an appropriate waste-to-energy (WtE) technology for Accra. The AHP methodology is used to assess four WtE technologies, namely landfill biogas, incineration, anaerobic digestion, and aerobic composting. Three main criteria and nine sub-criteria are identified for pair-wise comparison and assessed by 10 experts. The results show that incineration is the most preferred technology, followed by anaerobic digestion and aerobic digestion, with landfilled gas being the least preferred technology. Stakeholders in waste management development in Ghana can utilize the findings of the study to develop implementation strategies for capacity and institutional capabilities for both thermochemical and biochemical processes in the country.

Keywords: waste-to-energy; AHP; mega city; Accra; case study

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Citation: Agbejule, A.; Shamsuzzoha, A.; Lotchi, K.; Rutledge, K. Application of Multi-Criteria Decision-Making Process to Select Waste-to-Energy Technology in Developing Countries: The Case of Ghana. *Sustainability* **2021**, *13*, 12863. https://doi.org/10.3390/su132212863

Academic Editor: Elena Cristina Rada

Received: 22 October 2021
Accepted: 17 November 2021
Published: 20 November 2021

1. Introduction

Globally, about 33% of generated solid waste is not monitored or managed with broadly accepted techniques but rather is dumped into open areas that cause problems from both public health and environmental condition perspectives [1,2]. The World Bank reports that global solid waste generation was approximately 2 billion tonnes in 2017 and is estimated to be 3.4 billion tonnes by 2050. Considering these large quantities and their associated problems, cities urgently need to select appropriate methods to manage municipal solid wastes to address these local issues. Properly addressing the disposal of these wastes contributes to indirect progress concerning global greenhouse gas emission and transitioning towards global environmental sustainability standards. Efficient management of municipal solid waste also contributes to the economic development of a city or country. With multiple WTE technologies available, localities have a challenge when comparing the technologies for selecting which is more optimal for their circumstances.

Currently, various technologies may be used to recover energy from solid waste, and each technology has its own capacities, merits, and demerits. Therefore, it is critical to select appropriate technology or a combination of technologies to manage solid waste. It is challenging to choose the optimal technology because factors from many directions weigh on the selection process. A multi-criteria decision-making process (MCDM) can be helpful to decide the selection of the best technology suitable for solid waste management based on several usually conflicting criteria [3]. During this selection process, environmental, economic, and social aspects of energy recovery from municipal solid waste were considered.

The aim of this study is to identify and evaluate the available technologies used to dispose the solid wastes while considering the full complexity of factors weighing on the selection process. This study focuses on selecting the optimal waste-to-energy (WtE) technology for Accra, the capital city of Ghana, and its suburbs (Accra region). This selection of technologies contributes to Ghana's long-term wishes to get the solution to the management of solid waste through proper treatment and generating useful energy from the treated waste. In addition, such technologies support the closure of the carbon chain through developing the value chain with the production and utilization of waste while improving (protecting) the soil structure. Moreover, WtE technologies promote hybrid waste-to-energy plants in Ghana that create new jobs and sustainable solution for the solid waste disposal and management problems in the country. Furthermore, WtE technologies would contribute to saving a lot of emissions of environmental harmful gases each year in Ghana, which ultimately facilitates Ghana's climate change mitigation strategy.

The conversion of municipal solid waste-to-energy can be achieved with different technologies, which have different advantages and limitations. The key challenge is to find a suitable technology, taking into consideration the different criteria that can affect the selection process. Therefore, the selection of the appropriate WtE technology is a complex process that requires decision makers to evaluate different criteria and make the optimal choice for a particular setting. The analytical hierarchy process (AHP) is one the methods used by decision-makers for the selection process. In order to fulfil the study objective, an analytical hierarchy process (AHP), a multi-criteria decision-making (MCDM) method, was used. The AHP method supports to assess four WtE technologies, namely, landfill biogas, anaerobic digestion, incineration, and aerobic composting, using three main criteria and nine sub-criteria. Moreover, a pairwise comparison was done by soliciting 10 experts' opinions.

1.1. Solid Waste Management System: Importance to Environment

Environmental impacts associated with solid waste management can be evaluated through life-cycle-assessment activities. This assessment process generally reveals the intrinsic properties of the solid waste management systems from upstream to downstream. Such analysis also helps to evaluate various waste technologies, with respect to energy production or consumption and the amount of material recovery. For instance, with respect to incineration, landfilling sounds good for the environment due to extraction of gas. However, incineration offers energy recovery with higher efficiency than a landfill. Life-cycle assessment can offer more detailed evaluation of the environmental related issues, with respect to solid waste management systems.

Other available solid waste management systems show significant differences, with respect to the environment. For example, waste treatment through digested biomass technology may cause a potential toxicity impact on humans [4]. Any form of decomposition of solid waste causes environmental pollution due to inherent chemical compositions. In general, few landfills in the world can meet environmental standards that are accepted by the industrialized countries [5]. One of the major environmental concerns of decomposition of solid waste is the release of harmful gases that contribute to the greenhouse gas effect and climate change [6]. Additionally, various liquids released from solid waste, such as leachate, pose a serious threat to surface and ground water systems [5].

1.2. Sustainable Solid Waste Management System

Solid waste management systems are an important concern in today's environmentally conscious times. Enhanced attention due to legal restrictions, public awareness of hygiene and sanitation, and emergence of new technologies have brought many cities to the discussion table to consider their options for improved management. In order to protect the environment, it is now a global concern to manage solid waste towards sustainability. A sustainable solid waste management system can be defined as environmentally friendly, economically affordable, and socially acceptable for a specific region/country and its individual circumstances [7].

The level of sustainability varies from country to country that is also based on the economic situation. It is always recommended to plan for an integrated waste management approach to create a more sustainable waste management system. In addition, it is essential to analyse the situation of a solid waste management system and develop necessary strategic plans to determine and address the responsible factors to improve sustainability. It is a general practice to reduce material consumption to maintain sustainability. It is therefore suggested to the introduce 3R initiative, reduce, reuse, and recycle, to a solid waste management system to manage the material volumes [8].

1.3. Waste Management Technologies

As waste is no more treated as a garbage without value, different technologies are used to manage it in a sustainable way. All over the world, different technologies are used to manage waste in a more regulated and efficient way. The WtE technologies are used today to convert municipal solid waste (MSW) to energy and contribute to the protection of the environment. WtE plants use MSW as feedstock to produce energy in the form of heat to produce electricity [9,10]. There are three main WtE technologies based on their conversion pathways and their end-products: thermochemical, biochemical, and physicochemical [9,11,12], as seen in the Figure 1. The following sections describe the three main WtE technologies that are suitable for Ghana, as well as their pros and cons.

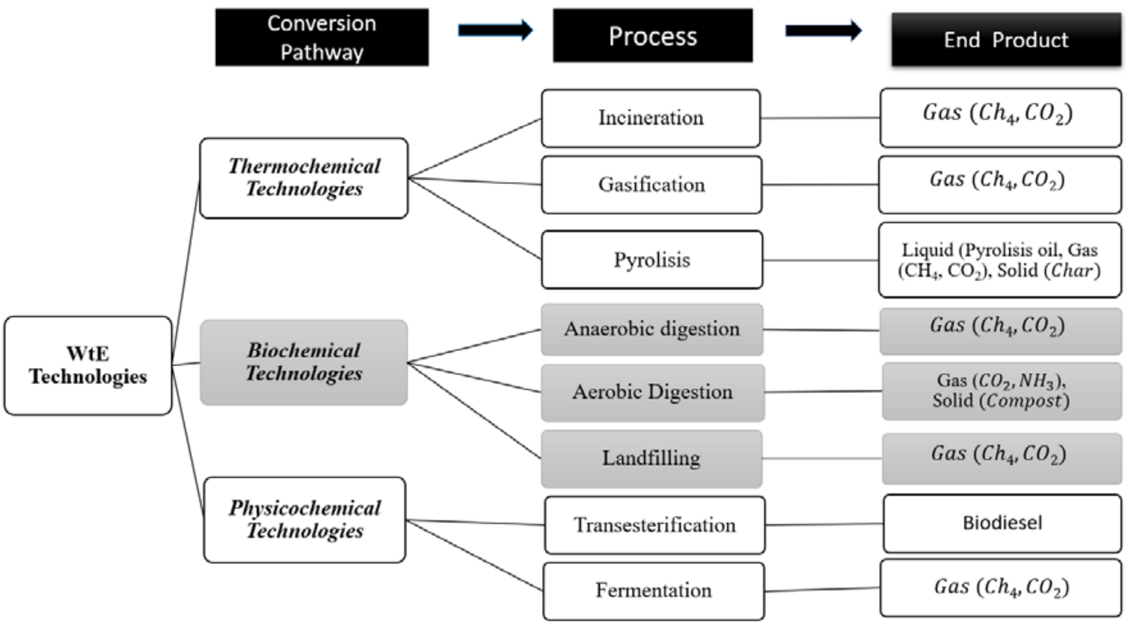

Figure 1. Summary of WtE technologies and their main end products (Source: Author).

1.3.1. Thermochemical Technologies

Thermochemical Technologies is a process in which the molecular structure of solid waste feedstock is broken down into smaller molecules at high temperatures to produce heat, electricity, and other valuable products. These technologies include incineration, pyrolysis, and gasification [12].

Incineration is a waste treatment technology that consists of the combustion of raw or unprocessed waste used as a feedstock [13]. Industrial plants used to incinerate waste are commonly called waste-to-energy plants. After the incineration process, the waste is converted into ash, flue gas, and heat. The flue gas is cleaned before being released into the atmosphere. In some cases, the heat is used by heat engines or power plants to produce electricity. The advantage of incineration over the other WtE technology is that it uses almost all types of MWS fraction and can reduce the volume of the waste by 80% and the solid mass by 70%. However, the initial costs to invest in such a plant is very high and could eventually lead to air and/or water pollution [14,15].

Pyrolysis is a thermal process that takes place without air at a temperature around 400–1000 °C, where the MSW is degenerated to produce gas (syngas), liquid (pyrolysis oil), or solid fuel (char) [16]. During the pyrolysis process, up to 80% of the carbonaceous fraction of the feedstock (here, MSW) used is recovered [14]. There are three types of pyrolysis reactions (slow, fast, and flash pyrolysis) depending on the operating parameters, such as temperature, heating rate, particle size, and residence time [15]. The proportion of each of the three fuels produced from the process depends on the type of pyrolysis used, as seen in the Table 1 [15,17,18]. However, pyrolysis technology has some demerits. Its capital, operation, and maintenance costs are high and it needs highly qualified professionals to operate. The adoption of this technology is very rare compared to other MSW management [14,15]. However, research by Higman and Tam [19] shows that, on a larger scale, pyrolysis is profitable economically and helps protect the environment by means of waste minimization and carbon capture.

Table 1. Percentage of each type of fuels for all three pyrolyses below (Source: Author).

Types of Pyrolysis	Gas	Liquid	Solid
Slow pyrolysis	30	35	35
Fast pyrolysis	50	20	30
Flash pyrolysis	75	12	13

Gasification is a thermal process that occurs at a temperature around 1000–1400 °C in an aerobic condition [16]. The main gasification reactors used in this process are rotary kilns, updraft fixed bed reactors, downdraft fixed bed reactors, bubbling fluidized bed reactors, entrained flow bed reactors, plasma reactors, vertical shafts, and moving grate furnaces [20,21]. During this process, the plastics and combustible organic fraction of the waste are converted into syngas or synthesis gas, such as carbon monoxide (CO), Hydrogen (H_2), carbon dioxide (CO_2), water vapor (H_2O), nitrogen (N_2), and methane (CH_4) [21]. At the end of the process, the clean syngas produced is used directly in gas turbines to produce heat and power [14]. However, gasification releases polluting compounds (alkalis, halogens, heavy metals, and tar). Some of the gases produced, due to their corrosiveness, need to be purified before being used [16].

1.3.2. Biochemical Technologies

Biochemical Technologies are processes in which biological agents or micro-organisms (yeast, for example) are used to convert organic parts of MSW into gas or liquid biofuel. The WtE technologies that fall under this pathway are anaerobic digestion, aerobic digestion, and landfilling [14,15].

Anaerobic digestion is a biochemical process in which micro-organisms are used to decompose the organic fraction of MSW. This reaction takes place in special reactors at a specific temperature and pH. The organic fraction of MSW is kept in a digester for 5–10 days, where different stages of anaerobic digestion take place. These stages are hydrolysis, acidogenesis, acetogenesis, and methanogenesis [15,22]. The major end product of this process is a high energy mixture of biogas (methane and carbon dioxide) and traces of sulphide and ammonia [23]. Anaerobic digestion technology has low capital and operating costs, as well as a low amount of greenhouse gas (GHG) emission, as compared to the thermochemical technologies. It is an efficient way to treat organic MSW. At the end of the process, a nutrient-rich substance produced by anaerobic digestion (digestate) can be used to make fertilizer. The drawback of an anaerobic digestion is that it requires a large area of land for the installation of the digestion plant. The management and maintenance of the plant is also difficult and expensive [14,15,24].

Composting is the method that decomposes biodegradable organic matter in a warm, moist environment by microorganisms in the presence of oxygen under controlled conditions [25]. The main factors that affect the composting process include oxygen, moisture, temperature, and nutrients. The end product, or compost, is a material rich in organic matter and nutrients that can be marketed as a soil amendment for agricultural and horticultural uses [26]. Mittal [27] described that on-site composting requires know-how, capital investment, sufficient space, and regular maintenance. There are different methods for aerobic composting, and selection depends on the type of biodegradable feedstock available and the goal of composting. The three recommended methods for composting are aerated static piles (windrows with perforated pipe constructed within the pile), bins, or aerated chambers. Windrows and aerated static piles are mainly used for high volume composting, while bins or aerated chambers are most typically used for small volume or home composting [28].

Sanitary landfill, also known as landfill, a tip, dump, rubbish dump, garbage dump, or dumping ground is a facility where non-hazardous solid waste is buried in order to limit its impact on the environment, according to local and international regulatory frameworks [29]. According to William and Larson, landfilling is slightly similar to anaerobic digestion. The technological approach of this method involves siting, design, construction, operation, and post-closure landfill management. As shown in Figure 1, a landfill is made up of a complex excavation, cover system, and other systems that interrelate to break down, compact, and stabilize disposed wastes. Over time, waste placed in a landfill breaks down due to biological, physical, and chemical processes [29].

Figure 2 shows a range of technical elements in a landfill. Some of them are landfill cells that are built either by excavation or by construction of cell containment burns. Since protecting the groundwater is a priority, a well-designed system made up of liners (clay, plastic, or both) and a leachate collection and management system is used. Landfills emit gas, which is mainly composed of methane, CO_2, and traces of organic compounds. A gas collection system is used to prevent any gas emission to the atmosphere. The collected gas is combusted by means of landfill gas flare or used to produce energy [29].

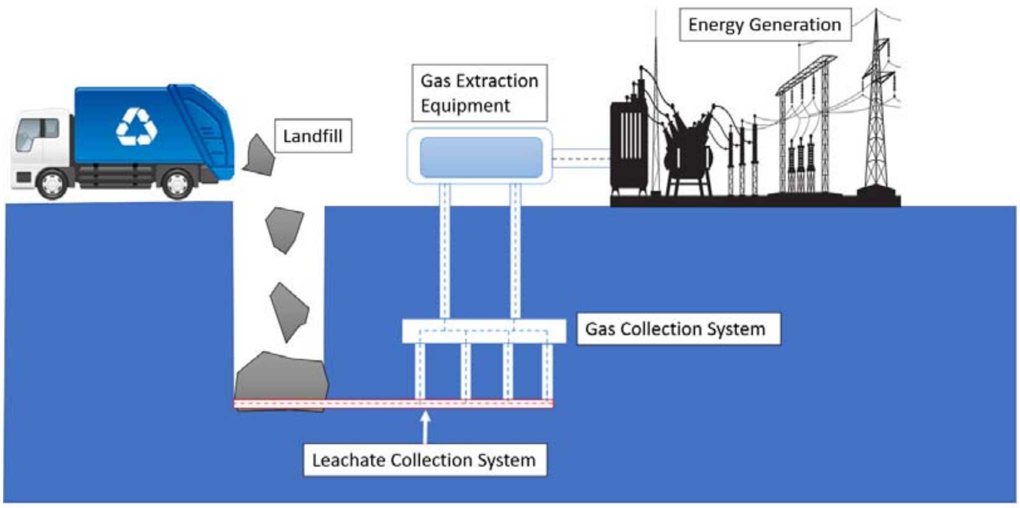

Figure 2. Principal technical elements of a landfill (Source: Author).

1.3.3. Physicochemical Technologies

The most popular physicochemical technologies used for WtE are transesterification and fermentation.

Transesterification is a process in which the fat fraction of food waste, especially used cooking oils and animal fats, are transformed into biodiesel [30]. During this physicochemical process, triglyceride molecules react with alcohol (methanol, for instance) in the presence of acid or base catalysts to produce biodiesel as the main product and glycerol as a by-product [31]. These biodiesels produced can either be used in transportation to replace petrochemical diesel or to produce electricity [32,33].

Fermentation is a metabolic process that uses microbes to decompose MSW organic material in an anaerobic condition. This process is suitable for MSW and has a moisture content of less than 75% [15]. The fermentation process is similar to the anaerobic digestion process, except for the methanogenesis stage. While the end product for anaerobic digestion is biogas, for fermentation it is liquid biofuel (ethanol) [15]. The ethanol can be used as a transportation biofuel in the place of gasoline [34]. Although fermentation processes use low-value waste and require less energy to operate, they produce high-quality fuel-grade liquid (ethanol), which is more environmentally friendly compared to gasoline. However, the fermentation process is slower compared to the anaerobic digestion process. The output needs to be purified (by distillation and dehydration), which is energy-intensive [15,34].

1.4. Identification of Factors to Select Waste Management Technologies

MSW treatment technologies vary from one country to another. There is no single technology that is suitable to manage all solid wastes [35]. In any case, it is important to follow the solid waste management approaches (Figure 3) because they outline the most environmentally friendly steps to take care of the waste before it is finally disposed of. The hierarchy stresses the 3Rs in waste management, specifically, reduce, reuse, and recycle.

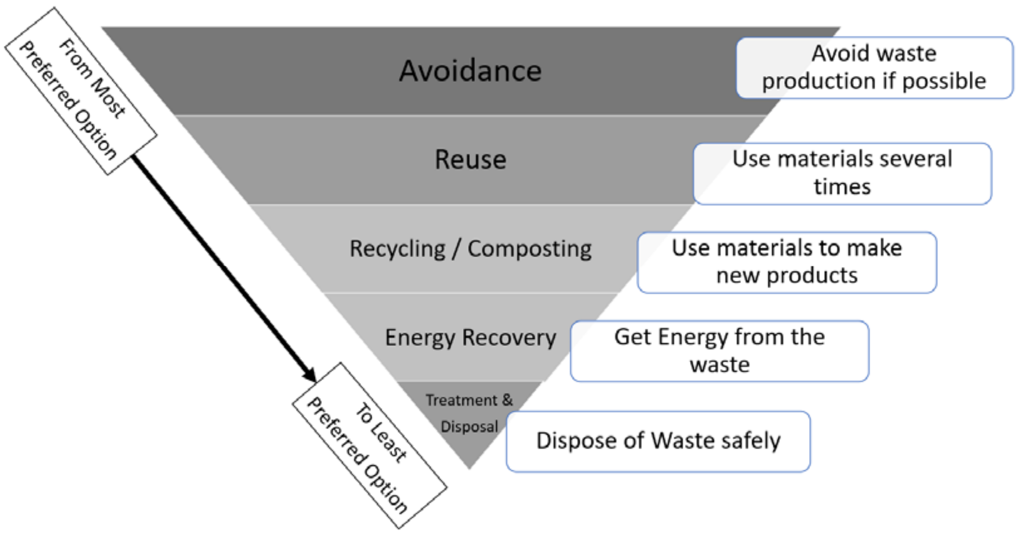

Figure 3. Waste management hierarchy (Source: Author).

Before decision-makers choose the optimal WtE, they need to consider the pros and cons of each technology. They should also consider the long-term economic impact, the nature of the waste, and the environmental concerns, as well the socio-cultural implications. Several studies have been conducted to help identify the best decision models for choosing sustainable and efficient waste management technologies, such as the cost benefit analysis model, the life-cycle analysis model (LCA), and the multi-criteria decision analysis (MCDA) model. Each model uses a different method and therefore has limitations. Some of them focus mainly on either monetary criterion (the cost benefit analysis model), environmental criteria and its impact on the whole life of the waste (the LCA), or environmental, economic, and social criteria (the MCDA) [36].

Other studies have confirmed that the MCDA model offers a subjective approach to assess sustainability of a waste management model since it effectively combines diverse issues, such as the environment, the economy, and society [37]. Among the MCDA techniques available, the AHP method developed by Saaty [38] is the most popular for technology assessment and selection in the renewable energy field [39]. Additionally, Oyoo [40] suggests that waste quality and quantity (WQQ) and social, environmental, technological, and economical factors should be included in this complex decision-making process. The renewable energy and waste management studies, with a focus on Ghana [41], indicate that the key criteria, such as economic, technical, human skills, and socio-cultural criteria, are required for the selection of WtE technology.

1.5. Municipal Solid Waste Management System in Ghana

As of 2020, Ghana has 16 regions divided into 260 local metropolitan, municipal, and district assemblies [42]. Currently, the population of Ghana is about 31.7 million [43]. Irrespective of any social and economic consideration, 0.2–0.8 kg/person/day of waste is generated by Ghanaians [44]. A study [45] published in 2015 estimated that 13,500 tonnes of solid waste were generated per day for a population size of 27 million. The same study gave an overview of the MSW characterization and quantification in Ghana. It showed the average generation of rate of fraction of household per capita and per day in Ghana, as seen in Figure 4. Figure 4 also shows that organic waste is the most generated waste in Ghana.

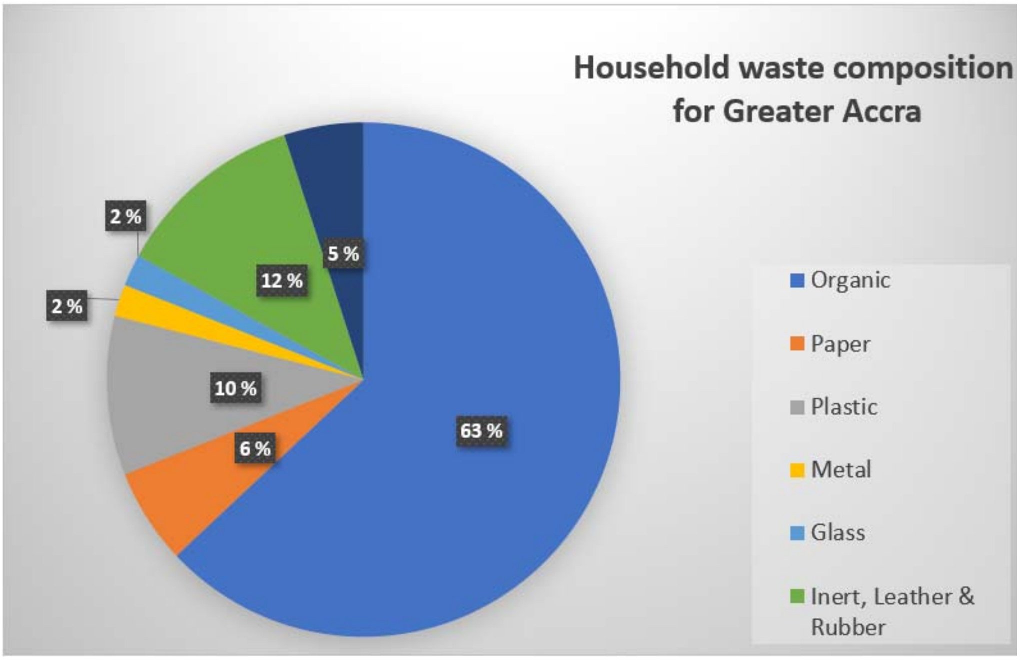

Figure 4. Average generation rate of fractions of household waste per capita per day in Ghana (Source: Author).

The municipal waste department established in 1985, with financial and technical assistance from the German Agency for Technical Co-operation (GTZ), was solely responsible for MSW management in Ghana. Although the collaboration with GTZ was helpful, their exit from the project deteriorated the waste management situation. It also showed the limit of the public sector in handling MSW. Therefore, the sector was decentralized, and calls were made for private waste companies to take care of the waste collection and management [46]. Currently, there are about 13 private WtE companies in Ghana operating in collection and disposal of waste [47]. Some of these companies provide house-to-house waste collection services. At the same time, some central containers are placed at a specific location where households dump their waste. These containers are later transferred to bigger designated dumping sites or landfills [46]. Studies by Manu [48] revealed that the methods used to dispose of solid waste in Ghana are still uncontrolled dumping of refuse, controlled dumping, sanitary landfilling, composting, and incineration. He also pointed out that uncontrolled landfills are often located at the periphery of an urban centre. However, in the rural areas and small cities, there are often neither waste collection systems nor landfills.

Waste is dumped at several uncontrolled dumping sites, which are sometimes located within the built-up areas and become a health hazard [48]. This is confirmed by data from the Ghana Statistical Service (GSS). According to the GSS, the method of disposal of solid waste in Ghana is done at 47.8% by public dumps, 19.5% is burned by households, 10.8% is dumped indiscriminately, and only 21.9% is collected by waste collecting companies [49]. Additionally, Addaney and Oppong [50] found that, like other developing countries, Ghana faces a serious challenge in managing its MSW because of poor infrastructure and lack of technical know-how. According to their study, despite effort by different governments to decentralise the waste management system and the adoption of a number of reform programs and policies, MSW management has been plagued by ineffectiveness. This has led to a poor waste collection system, such as inadequate storage containers, and disposal of waste in unauthorized areas in most municipalities in the country.

1.5.1. Available Solid Waste Management Technologies in Ghana

Studies by Ofori [51] showed that, due to the high organic content in the MSW in Ghana, there is a high opportunity for the WtE industry. In 2016, for instance, the energy that could have been generated from MSW amounted to 18.5 PJ, which is approximately 17% of the electricity consumption in Ghana [51]. The most used MSW management technologies in Ghana are composting, recycling, engineered and non-engineered landfills, and incineration; however, this is without properly capturing emitted biogas or any other by-products [51]. Among the aforementioned technologies, composting is one of the most used in Ghana. In a research conducted by Agro Eco Louis Bolk Institute, 16,000 tonnes of compost (estimated 60,000 tonnes/yr by now) was generated from MSW in 2016 only in the Greater Accra Metropolitan Area (GAMA). However, the technology, which tends to convert waste into energy by waste recycling, incineration, and electricity generation, is not well developed. However, there are a few commissioned or future WtE projects, as seen in Table 2 below.

Table 2. WtE projects in Ghana.

Project	Location	Objective	Status	Source
McDavid Green Solutions (MDGS)	Dawa, Greater Accra	Waste to Electricity	Planning	[52]
Armech Thermal Power Station Waste-To-Energy	Tema, Greater Accra	Waste burned to generate the electricity from several metropolitan and municipal assemblies in the Greater Accra Region. Capacity 60 MW	Planning	[53]
Spaans Babcock Waste, Energy, and Environment Project		Recycling of approximately 20 tons/day of solid waste, and incineration about 180 tons/day and produce 5 MW of electricity	Planning	[47]
Ghana/Germany Waste to Energy Plant	Atwima Nwabiagya in the Ashanti Region	Construct 400 KW Waste to Energy Plant	Planning	[54]
Hybrid Waste to Energy as a Solution for Ghana	Gyankobaah, Ashanti region	Build a 400-kW waste-to-energy plant	Future	[54]
Zoomlion waste recycling plant in each region	Each Region	Recycling plant in each region	Future	[55]

Another approach that is commonplace in Ghana is to turn the waste into compost, such as in the Kumasi Compost and Recycling Plant, which has been commissioned this year by the president [55]. Additionally, the Renewable Energy Master Plan (REMP) from the Ministry of Energy of Ghana showed the opportunities for WtE technologies and the target for years to come in reference to year 2015, as seen in Table 3 [56].

Table 3. Waste-to-energy potential in Ghana (Source: Author).

Technology/Intervention Utility Scale Power	Reference (2015)	2020	2025	2030
MSW + Biogas	0.1 MW	0.1 MW	30.1 MW	50.1 MW
Biofuel	0	100 t	5000 t	20,000 t

1.5.2. Waste Management Situation in Accra

Accra, the capital city of Ghana, has more than 2 million inhabitants and the Greater Accra region almost 5 million, according to the Ghana Statistical Service [57]. A total of 900,000 metrics tons of municipal solid waste (mainly organic waste at approximately 67%) is generated by Accra alone in one year [58].

Data from 2017 regarding the type of waste disposal method by type of locality and region show that 65.5% of waste is properly collected in the greater Accra region against 21.9% for the whole country. The pie chart below (see Figure 5) adapted from a census data from Ghana Statistical Service indicates that other waste disposal methods are used: waste burned by households (14.6%), public dumps (17.4%), and waste dumped indiscriminately (2.7%) [49].

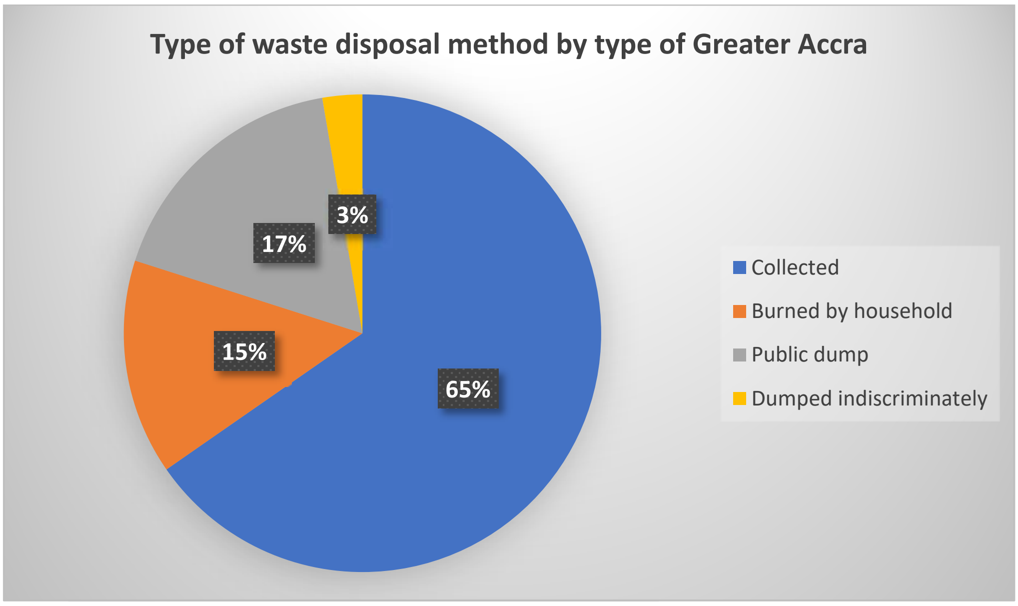

Figure 5. Adapted from census data from the Ghana Statistical Service (Source: Author).

The rest of the article is organized as follows: Section 2 describes the study methodology, while Section 3 highlights the study results. An intrinsic discussion, conclusions, and limitations are presented in Section 4.

2. Methodology

2.1. Identification and Selection Criteria of Waste Management Technologies

The goal of the study is to identify and evaluate the appropriate decision for WtE alternatives for Ghana. To our knowledge, no previous study has applied the AHP model to evaluate WtE options for Ghana. A literature review and discussion with key experts in waste management in Ghana was conducted to identify and select the criteria and sub-criteria and alternatives relevant to situation in Ghana [41,59–61]. After the review, three criteria, nine sub-criteria, and four WtE alternatives were selected for the study.

2.2. AHP Methodology

The AHP is a mathematical and subjective tool developed by Saaty [38] for analysing complex problems on different levels. The steps of AHP used in this study consists of four levels. The first step defines and states the objective of the problem, which is selecting the appropriate waste-to-energy technology option for Ghana. The second step is to decompose the objectives into three main criteria, namely environmental, technical, and socio-economic [59,62,63]. The third step further divides the main criteria into nine sub-criteria that provide additional details of the criteria (see Table 4). In the final stage, which is the four levels of the AHP, the alternatives will be evaluated with sub-criteria selected. In this study, the WtE technology alternatives are incineration, anaerobic digestion, landfill gas, and aerobic composting (see Table 5). The hierarchy model is presented in Figure 6.

Table 4. Description of the criteria and sub-criteria in the analytical process hierarchy (AHP) model.

Main Criteria	Sub-Criteria	Description
Environmental	Global warming (GW)	Capability of the selected technology reduce greenhouse gas emissions and other pollutants [64].
	Public and occupational health (POH)	Refers to ability the Selected WtE technology reduce the risks on public and workers' health (e.g., [62])
	Pollution potential (PP)	Refers to the selected WtE technology with least environmental impacts on water, soil, and air (e.g., [62,65])
Technical	Complexity of WtE technology (COM)	Refers to the WtE technology that is advanced technology and requires high skill level of labour (e.g., [59,63])
	Availability of skills (AS)	The current skills and knowledge available maintaining the selected WtE (e.g., [66])
	Grid availability (GA)	Refers to which of the selected WtE technology that can easily transmit at lower cost is considered better (e.g., [59,67])
Socio-economic	Capital cost (CC)	The selected WtE technology with the least investment cost (e.g., [41,59])
	Operation and maintenance cost (OM)	The selected WtE technology with the least operation and maintenance costs (e.g., [41,63,68])
	Job creation (JC)	The ability of selected technology to create the most job opportunities (e.g., [41,59])

Table 5. Summary description of the waste-to-energy alternatives used in Ghana.

Waste to Energy Alternatives	Description
Incineration (INC)	Incineration is a thermochemical conversion of the organic component of MSW into heat and power. The main output of an incineration plant is heat and hot flue gas.
Anaerobic digestion (ADP)	Anaerobic is a biochemical conversion of MSW to energy involving biological micro-organisms, such as yeast to convert the organic fraction of the waste into gaseous or biofuels
Landfill gas (LFG)	A sanitary landfill with a gas plant erected on the landfill to recover the gas generated as a result of anaerobic degradation of the organic fraction to produce heat or electric energy.
Aerobic composting (AER)	Composting is the method decomposing biodegradable organic matter in a warm, moist environment by microorganisms in the presence of oxygen under controlled conditions [25]. The end product, or compost, is a material rich in organic matter and nutrients that can be marketed as a soil amendment for agricultural and horticultural uses.

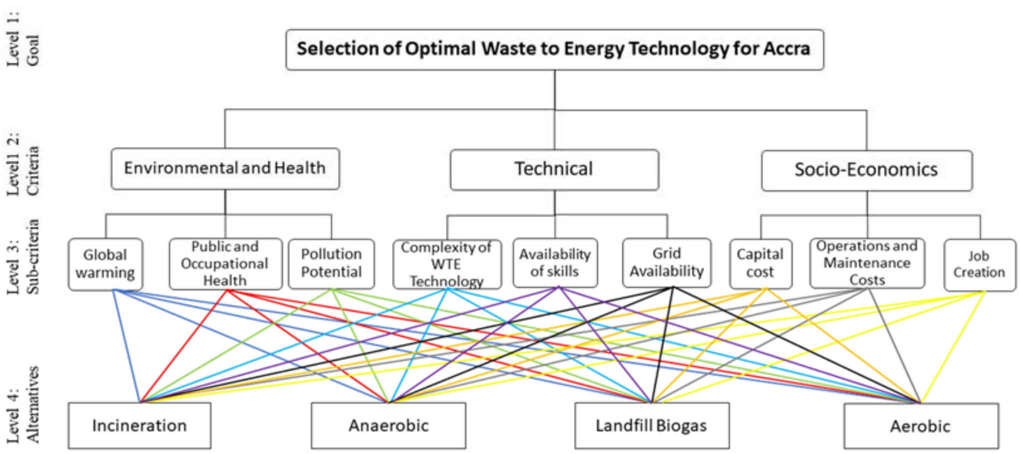

Figure 6. AHP Model for the selection of optimal waste-to-energy technology.

2.3. Collection of Expert's Opinions

Ten experts were asked to make pairwise comparisons between criteria and sub-criteria on a nine-point scale [38] (see Table 6). The AHP is usually employed with a small sample of experts who have local knowledge about the topic under investigation [69]. Table 7 provides information on the experts that participated in the questionnaire.

Table 6. Pairwise comparison scale for the AHP model (Adapted [38]).

Explanation	Numerical Scale
If option A (Criteria 1) and B (Criteria 2) are preferred equally	1
If option A is moderately more preferred than option B	3
If option A is strongly more preferred than option B	5
If option A is very strongly more preferred than option B	7
If option A is extremely more preferred than option B	9
Choose even number for intermediate evaluation	2, 4, 6, 8

Table 7. List of experts and their professions.

No.	Experts Category	Profession	Number
1	Academics	Professors and researchers with background in renewable energy and waste management	3
2	Waste Professional	Waste collection and disposal	1
3	Graduate researchers in bioenergy and waste management on Ghana	PhD researchers in bioenergy and waste management in Ghana	4
4	Energy Regulator	Energy developer and specialist in Ghana energy commission	1
5.	Decision Maker	Business manager in a waste company in Ghana	1

2.4. Construction of the AHP Model

A decision matrix to identify priority weights was constructed, consisting of the goal and sub-criteria, and scores of the experts are aggregated using the geometric mean. The following steps are followed to determine the normalized priority weights of the main criteria and sub-criteria: (i) construct a pairwise comparison matrices for all the criteria and sub-criteria; (ii) aggregate the comparison matrices; (iii) determine the relative weights of each criteria and sub-criteria using the normalized matrix. After that, the consistency of the pairwise comparisons are evaluated. The weights of the main and sub-criteria are estimated using Equation (1).

$$A_w = \lambda_{max}.w \tag{1}$$

where A is the comparison matrix, w represents the normalized eigenvector (priority vector), and λ_{max} is the maximum eigen vector. The consistency of the matrix is checked using the consistency ratio (CR) and consistency index. First, the consistency index (CI) is calculated using Equation (2), where n is the rank of the matrix.

$$C.I = \frac{(\lambda_{max} - n)}{n - 1} \tag{2}$$

Considering the randomness in judgement, the consistency ratio is calculated using Equation (3), where RI is the random index, which denotes the expected value of CI related to the order of matrices. If the consistency index is less than 0.10, the judgements of the experts are considered consistent and acceptable.

$$C.R = \frac{C.I}{R.I} \tag{3}$$

The standard values of RI are shown in Table 8.

Table 8. Random index (RI) values for different matrix sizes.

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.40	1.49

After checking the consistency of each comparison matrix, the local weights for the main criteria and sub-criteria are determined. The global weight of the sub-criteria is calculated as follows:

Global weight of a sub-criteria = local weight of the sub criteria x global weight of the corresponding main criteria.

3. Results

The results of the data collected was analysed using MS Excel. The responses of all of the 10 experts on the main criteria and sub-criteria were aggregated using geometric means. The results presented in Table 8 show the comparison matrices and priority vectors for the main criteria with a consistency ratio less than 0.1, indicating that the comparison matrices are consistent and the results can be accepted.

The results of pairwise comparison of the main criteria shown in Table 9 and Figure 7 show that environmental criteria (weight = 0.549) ranked the highest, followed by technical (weight = 0.241) and socioeconomic (weight = 0.241) criteria. These results demonstrate that the expert panel placed most importance on environmental factors while analysing the waste-to-energy alternatives in Ghana. These finding are consistent with those of Qazi et al. [15] and Kurbatov and Abu-Qadis [62], which also indicates that environment criteria ranked the highest when selecting WtE options.

Table 9. Pairwise comparison matrix for main criteria relative to the main goal.

Criteria	Environmental	Technical	Socioeconomic	Priority	Consistency Ratio
Environmental	1.00	2	3	0.549	0.02
Technical	0.5	1.00	1	0.241	
Socioeconomic	0.33	1.00	1.00	0.210	

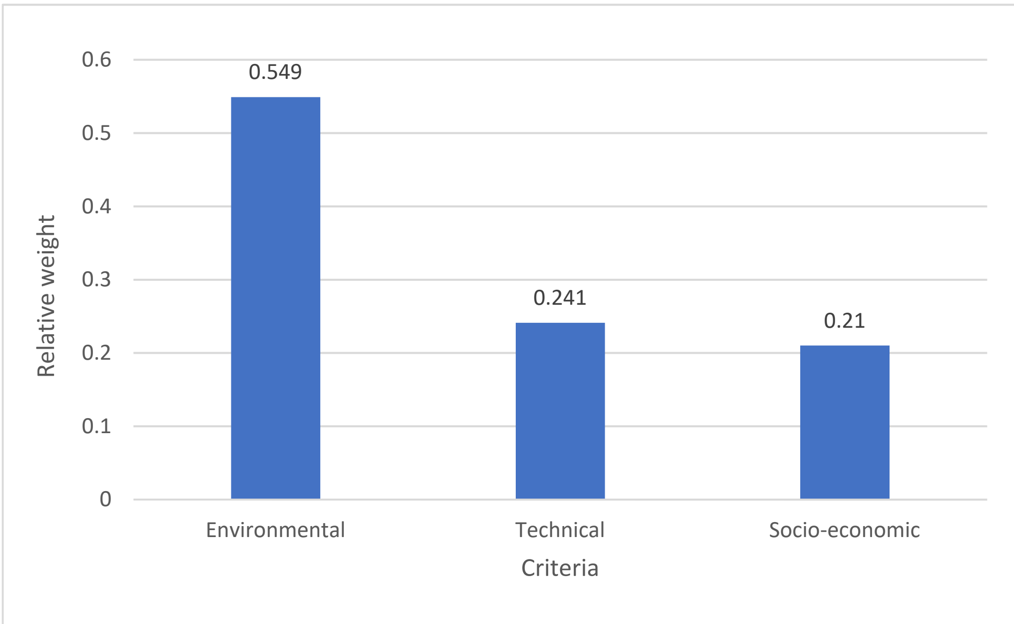

Figure 7. Priorities of the main criteria.

The results of the pairwise comparison of the sub-criteria, with respect to the main goal, are presented in Table 10.

Table 10. Analysis of sub-criteria.

Criteria	Environmental			Technical			Socioeconomic			Priority
Sub-criteria	POH	PP	GW	GA	ESA	COM	CC	OM	JC	
POH	1	2	1							0.411
PP	0.5	1	1							0.261
GW	1	1	1							0.327
GA				1	3	3				0.588
ESA				0.33	1	2				0.251
COM				0.33	0.5	1				0.159
CC							1	3	2	0.538
OM							0.33	1	2	0.297
JC							0.5	0.5	1	0.163

POH = public and occupational health, PP = pollution potential, GW = emission released by WtE plant (greenhouse gas impact), GA = grid availability, ESA = expertise skills available, COM = complexity of the WtE technology, CC = capital cost, OM = operations and maintenance cost, JC = job creation.

Under the sub-criteria associated with the environmental factor, public and occupational health (weight = 0.411) is found to be the most important, followed by global warming (weight = 0.327), while pollution potential received the least priority. These findings are consistent with those of Kurbatov and Abu-Qdais [15] and Khoshand [70], which indicates that public and occupational health received the highest preference.

Within the sub-criteria associated with the technical factor, grid availability (weight = 0.588) is ranked first, followed by expertise skills availability (0.251) and complexity of the technology (weight = 0.159). Agyekum et al. [66] found that the grid system is one of the major hindrances in developing renewable energy projects in Ghana.

Capital cost (weight = 0.583) followed by operation and maintenance (weight = 0.297) are ranked respectively under the sub-criteria of the socio-economic factor. The least ranked priority is job creation, with a weight of 0.163. The studies of Rahman et al. [71] and Oryani et al. [72] reported similar findings, indicating that capital cost is a key component in the evaluation of the socio-economic aspect of implementing waste-to-energy projects.

The next stage in the pairwise comparison considers the assessment of the WtE alternatives based on the sub-criteria (see Figure 8). The findings show incineration and anaerobic digestion as the preferred choice of technology that have the least impact on public health, followed by aerobic digestion. Landfill gas was the least preferred choice. Considering the technology with the least pollution potential, the suitable choice is anaerobic digestion, followed by aerobic digestion, with landfill gas as the least preferred choice. Under the global warming potential, incineration and landfill are observed to be the WtE technologies with the greatest impact.

Based on the sub-criteria of grid availability (GA) incineration was ranked first with a weight of 0.50, followed by landfill gas (0.24). The anaerobic digestion was ranked as the third option, followed by aerobic digestion. The key outputs of incineration plant, which are usually located in the urban areas, are electricity and heat. In Ghana, the grid availability is more efficient in urban than in rural areas, making it easier to transmit the electricity produced by the incineration plant. On the other hand, biochemical technologies, such as anaerobic digestion, which are suitable for rural areas (e.g., [63]) with inadequate grid availability, can make energy delivery very challenging.

Under the sub-criteria of expertise skills availability, the landfill gas received the highest rank, followed by incineration, while anaerobic and aerobic received the least choices. The finding is similar with that of Kurbatov and Abu-Qdais [62], who reported that skills availability for landfill gas received the highest rank in Moscow. Incineration ranked second, which is consistent with the analysis of Farooq et al. [63], who suggest that the low level of labour skills required for incineration makes it an ideal choice for developing countries like Ghana. The WtE technology with the preferred least capital cost was aerobic digestion, followed by landfill gas. Incineration was identified as the least preferred under criteria related to the capital cost, but incineration ranked the highest under the criteria with the least operation and maintenance expenses. The cost to operate incineration includes the cost of labour and the absence of sorting the waste, which may explain the reason for the preferred choice. Aerobic digestion was the least preferred choice under operation and maintenance, making it the most expensive. Aerobic digestion has high operation and maintenance costs because the separation of organic waste from the mixed municipal solid is not an effective process in Ghana. The separation process is a critical aspect of obtaining the inputs for aerobic digestion (e.g., [41,73]). Within the job creation sub-criteria, aerobic digestion is found to be the most preferred, with a weight of 0.41, followed by incineration (weight = 0.35). The least preferred option is landfilled gas.

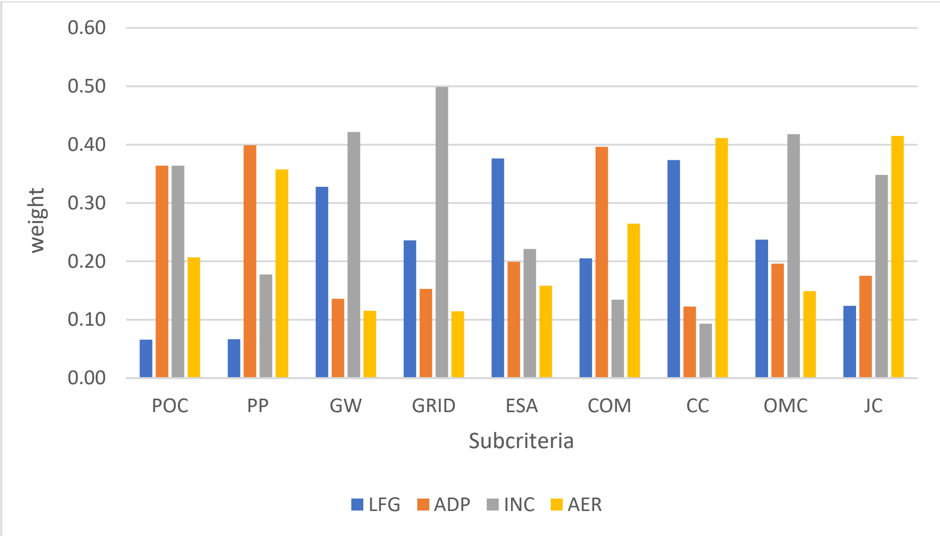

Figure 8. Priority of waste to energy technologies based on the sub-criteria.

In the final step, the global priorities of the WtE alternatives are determined by combining the local weight of all the criteria, sub-criteria, and the alternatives. The overall priorities, presented in Figure 9, show that incineration is the best alternative, with a global weight of 0.32, followed by anaerobic digestion, with a weight of 0.26. The third ranked choice is aerobic digestion, with landfill gas as the least preferred choice.

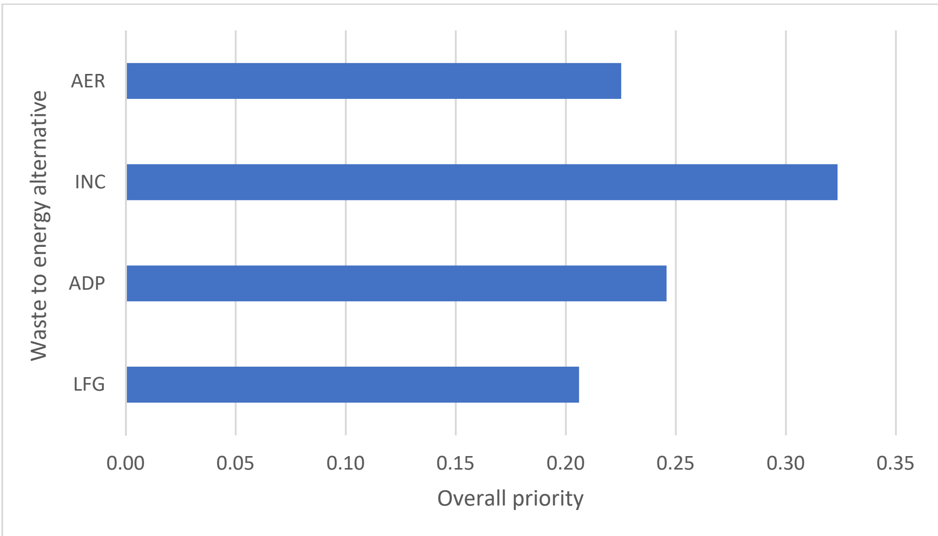

Figure 9. Global ranking of waste-to-energy technologies for Accra.

4. Discussion and Conclusions

The conversion of municipal solid waste for energy generation is becoming an important discussion in the world. Waste generation in Accra is creating a need to explore the selection of waste-to-energy technologies that are appropriate. The selection of WtE technologies require the consideration of different factors and stakeholders. The goal of the study is to use the AHP methodology to select the appropriate technology for the city of Accra. The main criteria and sub-criteria are selected considering the relevant factors to Ghana, and four waste-to-energy technologies are ranked. The results show that incineration is the most preferred WtE technology, followed by anaerobic digestion. The low complexity and low skills requirements of incineration technology (e.g., [34]) is an appropriate WtE option for Ghana. Compared to other thermochemical processes, such as gasification and pyrolysis, the capital cost and operational costs of incineration is lower. Despite these advantages of incineration plants and abundance of waste, the design of incineration plants in Accra and other parts of the country is lacking. The institutional and governance capabilities should be improved to encourage investors to develop and implement an incineration plant in the country. For example, the development of incineration plants should be located within the strategy of the development plans of the city of Accra. In addition, the city of Accra should develop suitable waste collection systems to ensure guaranteed feedstock for developing incineration plants. Both anaerobic and aerobic digestion are potential options in Accra. The issue of grid availability shows that both WtE options are ideal for the rural communities where the production of agriculture waste is dominant. The location of these options near the communities would lessen the pressure of a grid as they would be closer for transmission of electricity.

The environmental criteria scored the highest in the main criteria, suggesting a need for transparent laws on pollution prevention and environmental-related assessments of waste-to-energy projects in Ghana. Increasing the awareness of the health aspects of waste may increase the cooperation of residents in waste collection and disposal, which is critical for the development of incineration plants.

The limitation of the study is related to the selection of WtE options. For example, there are different types of aerobic digestion, and our study considered aerobic digestion in general. Future studies can consider different methods of aerobic digestion and its objective. Although socio-economic criterion is the least favoured option of the main criteria, future sub-criteria, such as tipping fees, which is a critical component in financing WtE processes in developing countries, such as Ghana, should be evaluated using AHP models.

The selection of WtE technology involves different stakeholders and a complex decision process. Our study contributes to this process by providing relevant criteria, information, and analysis to assist decision-makers in selecting appropriate WtE options for the city of Accra.

Author Contributions: The research was designed and performed by A.A., A.S., K.L. and K.R. The data were collected and analyzed by A.A. The paper was written by A.A., A.S. and K.L. and finally checked by K.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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