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Location-allocation combining fuzzy analytical hierarchy process for waste to energy facilities siting in developing urban areas: The case study of Lomé, Togo

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ABSTRACT

Waste facilities siting is one of the complex problems encountered by decision makers of waste management in urban developing areas. Waste to Energy (WtE) facilities siting alongside transfer stations involves a Multi-Criteria Decision Analysis (MCDA) and has leveraged waste value chain. However, the process requires to consider the interlinked fields of environment, socio-cultural and economic/technical factors as Geographical Information Systems (GIS) in a context of lack of knowledge and expertise. This study aims to propose a framework of WtE facilities siting through a GIS-based Fuzzy Analytical Hierarchy Process (FAHP) and location-allocation method in Lomé's case study in Togo. This method was applied with boolean logic and fuzzy overlay operators, to assess the potential sites and optimize their selection through a location-allocation solver considering transfer stations and road networks under ArcGIS. Moreover, WtE technologies were attributed to sites based on the territorial aspect. As result, 30.70% of the study area was excluded and three potential areas with a minimum value of 3.47 km^2 comprised between 0.81% and 1.01% of the study area, and have been obtained with an acceptable consistency ratio of 0.09. The potential sites are more influenced by slope and residence criteria under economic/technical and socio-cultural factors, with 29.13% and 19.84% of weight respectively. Therefore, through the location-allocation method two optimized sites are obtained and assigned to transfer stations; the first suitable site close to industrial area is appropriate for the gasifier which consequently classified ahead of the anaerobic digester that is suitable for the second suitable site close to agricultural area. As result, prioritizing WtE technologies and site selection should take into account territory aspect, waste sources as well other environmental, socio-cultural and economic/technical factors. This approach has demonstrated its robustness and serves as a stepwise tool for decision makers in WtE facilities siting in developing urban areas.

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1. Introduction

The high demographic growth rate in developing countries and the population needs for settlement have raised and are expected to increase in the next coming decades [1]. In addition, people's migration from rural to urban areas leads to high pressure on land use and habitat. Indeed, an urban area is an entity of a local administrative zone of about ten thousand inhabitants while its agglomeration counts for half of the inhabitants where the residential, commercial, and institutional buildings are contiguous within a threshold of 200 m, with an exception made for waterbody, park, road network, etc. [2]. Hence, the dynamic of population growth and habitat needs has led to the extension of urban areas through peripheric zone development in developing countries. Such cases are illustrated in Africa with an urban growth rate of 3.55% per year which is expected to be maintained by 2050 [1].

The growth of urban areas is characterized by the development of socio-economic factors while occurring health and environmental risks to well-being. In fact, urban solid waste generated by human activities is one of the most important sources of pollution and contributes to climate change [3]. Indeed, its mismanagement particularly in developing countries, has led to socio-economic, environmental, and health risk issues over decades. For instance, under certain dramatic circumstances with a lack of sanitation regulations, dwellers either burn or dispose of their waste respectively in open air and water which leads to Greenhouse Gas (GHG) emissions, as well as air, soil and water pollution [4]. Whereas, such waste amount generated has many alternative potential ways to harness for either material or energy recovery to sustain countries' development [5].

Accordingly, African countries especially in the Sub-Sahara region with low Gross Domestic Product (GDP), have the lowest coverage rate of waste collection. It has ranged between 50 and 70% through municipalities services, according to Cointreau-Levine [6], and could be high depending on the municipalities' financial capacities as about 90% for Surabaya, Bogotá, Comas, and Delhi cities, even reaches 100% in wealthy neighborhood like Surco in Lima [7]. With about 0.4 kg/day/capita in Antananarivo, 0.6 kg/day/capita in Lomé, Delhi, and Surabaya, and 1.0 kg/day/capita in Bogotá for solid waste generation rate as reported by Mathieu et al. [7]; the collection system still being insufficient generally due to rapid urbanization growth in peripheric zone of cities that goes without required infrastructures, logistics, and politics. For instance, in Lomé about 42.1–44% of solid waste collection rate respectively in 2005 and 2011 were recorded and disposed of in the sanitary landfill [5,8], while most of the remain continues to spread in unproper manner. Therefore, to handle urban solid waste management, many efforts are made and have consumed about 10%–20% of the municipalities annual budget. In addition, people with low revenue persist on the traditional way to dispose of their waste in unlawful dumpsites which are out of the collection services through Non-Governmental Organizations (NGOs), associative groups, private companies, etc. [9]. Moreover, the remote urban areas of Togo such as Kara, Sokodé with respectively 0.41 and 0.54 kg/day/capita [10,11], have developed alternatives to reuse the organic fraction either for feeding livestock or composting in agricultural activities. Such methods help to relieve municipalities' budget for solid waste collection in those urban areas resulting to a low collection rate of about 27.80%–28.50%, but still facing unlawful dumpsites which create pollution and health risks [11]. Those dumpsites often closed to dwellers who did not subscribe to waste collection services, are source of health risks and environmental pollution such as waterbody and groundwater table contamination leading to diseases (e.g., cholera, diarrhea, etc.) [12]. Also, the lack of logistics combined with a lack of road network and non-structured residential buildings [7]; and last but not least, the land availability and cost for siting waste facilities [13]; have led to inefficient solid waste management, especially in Togo.

On the other hand, the utilization of waste like renewable sources [14], for electricity as well as alternative fuels, can sustain solutions by mitigating environmental impacts and offsetting fossil fuel in energy sectors [15]. Waste to Energy (WtE) facilities development and siting as other facilities have been largely discussed and reviewed in many studies regarding the potential from diverse feedstock [14]. The energy recovered through any process is likely to be heat, electricity, and alternative fuels in form of gas, liquid, or solid as end products and could help to achieve cities' development and sustain waste management in line with the agenda 2030 of the United Nations for Sustainable Development Goals (SDGs).

Therefore, waste facilities siting is subsequently reviewed to well address the avenue for waste management system. First of all, transfer stations play an intermediate role between waste sources and landfill or conversion facilities, and its siting has been discussed largely through a Multi-Criteria Decision Analysis (MCDA) to plan waste management in urban or metropolitan areas [16]. The Geographical Information Systems (GIS) based MCDA is a way to combine geographical data and decision makers preferences into relevant information for decision making, according to Malczewski [17]. Such techniques are widely used by waste management stakeholders in decision making process for sound reflection in the evaluation of various criteria related to many domains involved, to solve waste facilities siting and related problems [18]. Indeed, waste facilities siting as well as landfill, waste treatment plant, etc., have been studied by many researchers through the technique of MCDA to well address the multi-objectives issues encountered in such processes [19–25]. Eskandari et al. for locating landfill, used environmental, economic, and socio-cultural constraints as criteria and came out with the suitability map which was validated by field visit [21]; while the environmental, socio-economic, geological and geomorphological criteria were used by Al Khaldi et al. [26]. Also, Trust Nhubu et al., assessed in their study with the help of MCDA the suitability sites of transfer stations for future municipal solid waste management within and surrounding Harare urban city in Zimbabwe. Thus, a variety of MCDA methods like Weighted Linear Composition (WLC), Analytical Hierarchy Process (AHP), and Fuzzy Analytical Hierarchy Process (FAHP), have been used for municipal waste management issues as reviewed by Khan and Samadder [23]; where the fuzzy membership set has been used commonly for criteria standardization due to its capability of managing uncertainty and imprecision in data [27]. In addition, to enhance the criteria evaluation for sites selection the qualitative and subjective aspects were introduced under a fuzzy environment by Önüt and Soner [28], through a combine fuzzy Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) with AHP. The Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE), TOPSIS and ELECTRE are often applied when decision-makers focus on ranking the alternatives rather than carrying an optimization process of solutions [29]. Moreover, the decision tree technique has been deployed on a large set of criteria by Alanbari et al. [22] for the landfill site selection problem in Irak. Hence, to optimize and reduce the cost of solid waste collection route from sources to transfer stations, landfill or any other waste facilities, a location-allocation method coupled with GIS was used several times in siting such communities' facilities [30–32]. Particularly, for WtE facilities siting process, well-known and established technologies from several studies on technology selection through the use of AHP regarding benefits, opportunities, cost, and risks criteria are required [33]. WtE technologies selection such as biochemical, thermochemical, and physico-chemical processes were performed by Qazi et al., with the usage of MCDA for optimum options [34]. Furthermore, Kurbatova and Abu-Qdais [35], reviewed municipal solid waste management and energy sector of Moscow's city and its suburbs for the best WtE technology options through AHP based on environmental, technical and socio-economic criteria without territorial aspect factor. The anaerobic digestion technology is ranked the best among other technologies for electricity generation in Nigeria, through the use of TOPSIS technique by Alao et al. [36]. In addition, several methods have been applied under various conditions such as fuzzy DEMATEL in China by Wang et al. [37], AHP in Egypt by Abdallah et al. [38], AHP-fuzzy TOPSIS in Ghana by Afrane et al. [39], in the WtE technologies selection process and again came out with anaerobic digestion technology as the most suitable. However, Farooq et al. [40], highlighted the importance of incorporating territorial aspect as well as environmental, socio-economic, technical, waste origin and type criteria, to cope with a suitable framework of WtE technologies selection in any given region.

Accordingly, from the reviewed studies, WtE facilities siting alongside transfer stations by incorporating territorial aspect is rarely discussed as introduced by the geologist Jean Gouhier, like new geology's field termed rudology (i.e., the study of waste management regarding territorial aspects) [40]. Therefore, this study has assumed that a new modeling approach of WtE facilities siting alongside transfer stations through the location-allocation combine with FAHP method could improve significantly waste management system and mitigate the related complex issues abovementioned. The aim is to propose a general modeling framework of WtE facilities siting in developing urban areas regarding territorial aspect, transfer station locations, technologies and waste stream specificities to strengthen material and energy recovery for sustainable development.

2. Methodology

This section provides step by step processes that have been carried out to find the suitability sites for locating WtE facilities alongside transfer stations to sustain solid waste management considering environmental, socio-cultural, and economic/technical criteria. The GIS based FAHP and location-allocation approach for sites suitability was developed as a robust route to plan a sound framework of solid waste management in developing urban areas as shown in the flowchart in Fig. 1.

2.1. Waste to energy technologies selection

WtE technologies have been compared regarding numerous factors such as waste composition, territorial aspects, technical aspects

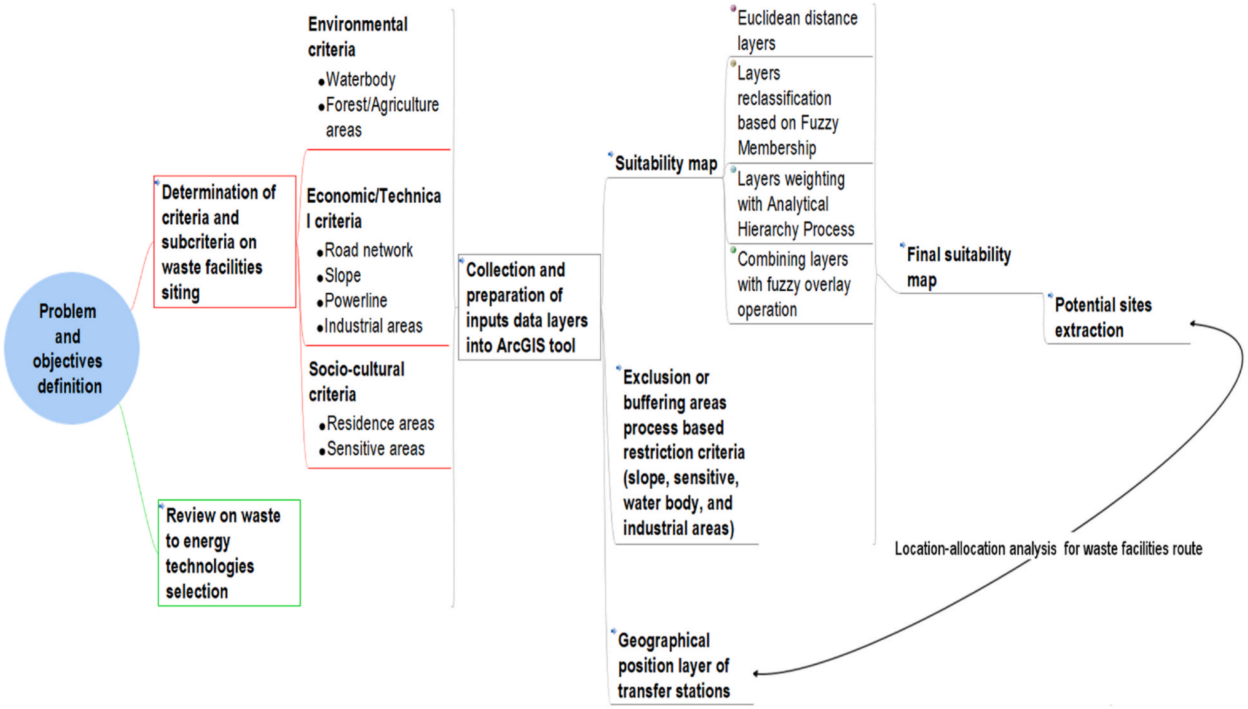


Fig. 1. General flowchart of WtE facilities siting process.

and framework conditions, according to Farooq et al., in the technologies selection analysis. The anaerobic digestion and/or gasification processes have been chosen on the basis of Lyfe Cycle Assessment (LCA) and Lyfe Cycle Cost (LCC) of WtE technologies as reported many studies [40–45]. This is done regarding solid waste fractions, which are classified in two waste categories such as biogenic or biodegradable (e.g., food waste, garden waste, wood, and paper/cardboard), and non-biogenic or inorganic combustible fractions like plastic, rubbers, etc. [46]. Whereas, the non-combustible inorganic waste fractions (e.g., metals, glass, dust, soil, and bricks, etc.) are not considered under any WtE technologies due to the fact that it results to solid slag or bottom ash formation during conversion [47]. As result, the anaerobic digestion in peri-urban or rural areas is a most suitable way to convert organic waste into biogas and compost while in industrial urban area gasification is most suitable. Furthermore, fuel generated can be taken for electricity or end used product; while compost can be used as fertilizer for urban agricultural activities [39,46].

2.2. *GIS-based FAHP analysis*

This section provides overall suitability analyses under ArcGIS environment, by incorporating remote sensing and ground data collected during the investigations. The point, vector and raster data formats regarding their availability and importance have been considered through the FAHP combined with location-allocation method to establish the suitable sites of WtE facilities. This was based on criteria selection, restriction and suitability analysis to find the suitable sites to develop WtE facilities.

2.2.1. *Criteria selection*

Siting waste facilities requires a number of criteria to be considered in order to build safe and sound framework that involves all stakeholders of waste management. The criteria used in this study, were categorized in three main fields such as environmental, socio-cultural and economic/technical, regarding the required condition to fulfill waste facilities siting as mentioned throughout the literature [16,19,21,24,26,27], [46–50]. The criteria defined through data collection were as follows: residence, industrial area, forest/agricultural area, waterbody, slope, road network, sensitive area, and powerline. They were used in the subsequent sections for restriction and suitability sites analyses.

2.2.2. *Restriction analysis*

The restriction map was based on four criteria to screen out of the study area the places that are not allowed for waste facilities development through the boolean overlay technique. It consists of using raster data by assigning the grid cells the boolean values zero (0) and one (1) respectively for the areas that are not acceptable and acceptable. Hence, it has considered the economic/technical (i.e., slope and industry area), environmental (i.e., waterbody) and socio-cultural (i.e., sensitive area) restrictions as important like mentioned in the literature [48–54].

$$R_{E,i} = \prod_{k}^{n} R_{i,k} \tag{1}$$

Where $R_{E,i}$ is the boolean value of the ith cell of the final restriction map, $R_{i,k}$ is the boolean value of the ith cell in the kth restriction grid layer, and n is the number of restriction criteria considered.

2.2.3. *Suitability analysis*

2.2.3.1. Fuzzy membership set. This method is applied herein to reduce uncertainty and due to the continuous aspect of geographical data used within a context of lack of regulations and sound framework in siting waste facilities in developing countries. Therefore, this study has based the analysis of raster data classification on the fuzzy membership set for standardizing the criteria [55,56]. The raster data are resulted from the conversion process of vector data through the euclidean distance toolbox. Hence, the inputs parameters of fuzzy membership set and its function type were based on the sensitive control points for siting waste facilities. Thus, the data were reclassified and normalized through the commonest and recommended linear fuzzy function widely used due to its simplicity and dependence on non-chaotic input parameters among other functions (i.e., small, large, gaussian, etc.) [47,57,58]. It consists of reclassifying the information contained in grid cells into a value scaled from “0” to “1”, where “0” stands for location not suitable and “1” stands for location most suitable. The following equation (2) expresses the triangular Membership Function (MF) with three sensitive control points (a, b, c) from which high or low fuzzy values are obtained through linear increasing or decreasing constant rate [28].

$$MF(x,a,b,c) = \begin{cases} 0, x \le a, c \le x \\ (x-a)/(b-a), a \le x \le b \\ (c-x)/(c-b), b \le x \le c \end{cases} \tag{2}$$

Where *a, b* and *c* respectively increase in terms of parameters values giving the values of *MF* ranged between “0” and “1”.

2.2.3.2. Fuzzy overlay. The normalized input rasters are used in this section to assign a relative weight of criteria through the AHP, which allows to rank their relative importance in siting process through the Pairwise Comparison Matrix (PCM) based on the fundamental scale of Saaty [59]. Hereafter, the PCM was established through a review on relative importance of criteria based on expert opinion found in the literature [30,46,48,58], through the process of siting WtE facilities. To check the consistency of the matrix built, the Consistency Ratio (*CR*) is computed under Microsoft Excel environment through equation (3) as follows:

$$CR = CI / RI \tag{3}$$

Where *CI* is the Consistency Index, and *RI* is the Randomness Index.

Otherwise, *RI* is defined from Saaty's *RI* standard values [60] and the *CI* is computed through the following equation (4):

$$CI = (\lambda - n) / (n - 1) \tag{4}$$

Where n and λ are respectively the order and the eigenvalue of the PCM.

After the PCM is validated, rasters are ranked and assigned to a relative weight, the criteria layers are overlaid to get the suitability map. Therefore, this study has considered the fuzzy overlay method in this process owing to its flexibility to combine the criteria weighted compare to the boolean and weighted overlay methods. There are several fuzzy overlay operators such us fuzzy AND, fuzzy OR, fuzzy product, fuzzy sum and fuzzy gamma. However, fuzzy sum is applied to combine criteria layers weighted and find all possible suitable locations considering altogether criteria in line with the aim of this study. Hence, equation (5) demonstrates the overlay operation as follows:

$$\mu(x) = 1 - \prod_{i=1}^{n} (1 - \mu_i) \tag{5}$$

Where μ_i is the fuzzy MF for the ith criterion layer, $i = 1, 2, \ldots$, n and $\mu(x)$ is the output membership values.

2.3. Location-allocation analysis

A location-allocation method, is applied on the potential suitable sites, extracted from suitability analysis, and the existing transfer stations to allocate within the study area. This process optimizes sites selection considering road network data under Network Analyst tool. The final sites chosen are based on minimizing the impedance (i.e., distance or time) for a given transport speed between the demand points (i.e., transfer stations) and WtE facilities with equal weight assumed. As a matter of fact, the shortest routes are found through the location-allocation solver considering the road network, and from potential sites, the best ones are assigned to demand points. Ultimately, the technologies of WtE facilities are defined considering the closest site selected to industrial area to be gasification and the closest site to agricultural activity to be anaerobic digestion as reviewed.

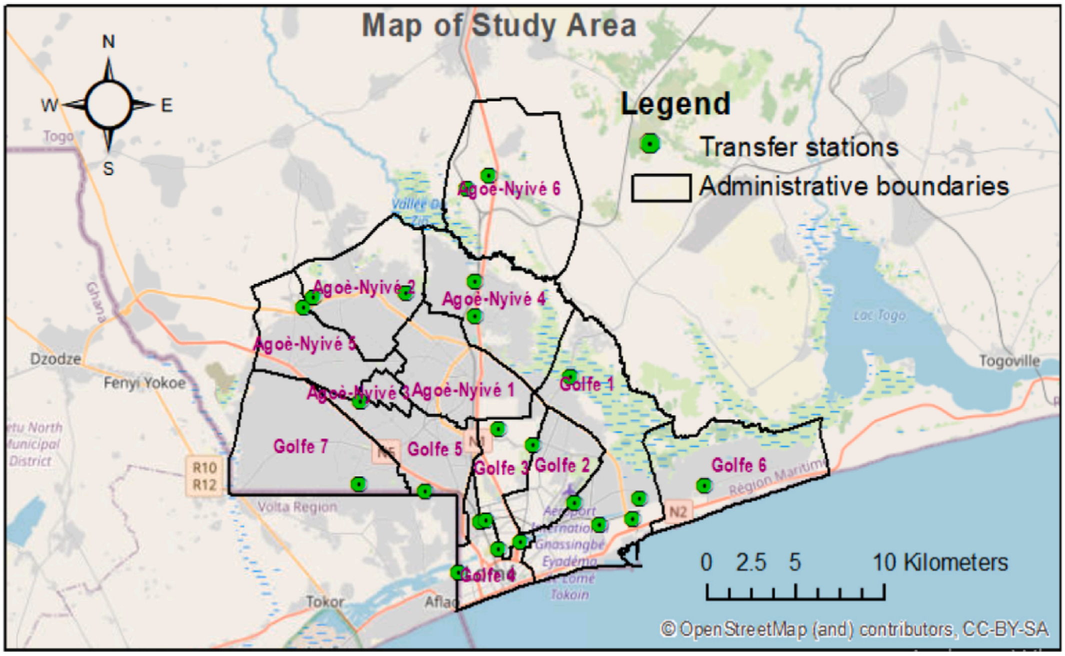
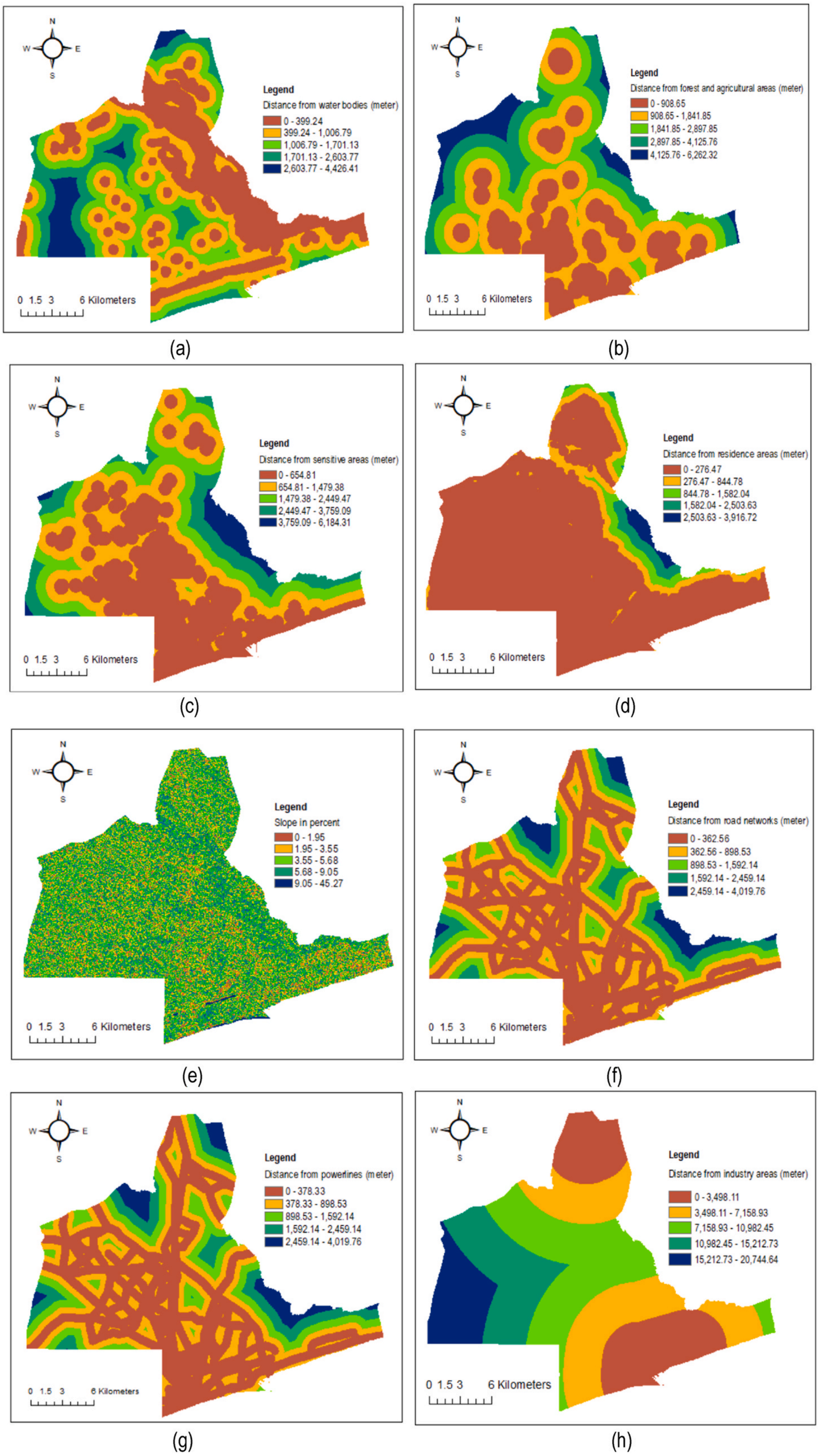


Fig. 2. Transfer stations locations in Lomé.



(caption on next page)

Fig. 3. (a) Waterbody areas buffering (b) Forest/agricultural areas buffering (c) Sensitive areas buffering (d) Residence areas buffering (e) Slope of the terrain (f) Road network buffering (g) Powerlines buffering (h) Industry areas buffering.

3. Case study: city of Lomé

3.1. Study area and state of the art of solid waste management

Located between longitudes 1.08°–1.38° east, and between latitudes 6.11°–6.36° north, Lomé is the capital of Togo with an area of 425.6 km^2 [61]. This choice is based on the following reasons: (i) it faces high environmental pressure from solid waste frequently dumped in open air or at transfer stations (ii) landfill is practically the only current formal alternative for solid waste management, (iii) planning of waste facilities development to decrease solid waste pressure on public health, environment and harness their added values. Indeed, an assessment was carried out in the months of August and September 2022, to assess thoroughly solid waste management system on the territory of Lomé.

Consequently, Lomé has the highest budget in terms of solid waste collection compare to other urban areas in the country, even higher than other cities such as Delhi, Surabaya, Antananarivo, and Bogota; while solid waste collection and its valorization still being inefficient in such cities [7]. Since 2018, Lomé was extended and its collection services demands for solid waste generated have increased. There are two ways of solid waste collection, either collected directly from sources, mostly in wealthy neighborhood, to landfill or indirectly collected from sources to transfer stations in middle and low-income neighborhood and then conveyed to landfill. The stakeholders involved in these collection services are from private compagnies, NGO's, etc., across the 13th local government areas, under the control of ANASAP and DAGL which are public institutions responsible of waste management respectively in the local government areas of Agoè-Nyivé and Golfe. A wide solid waste stream composed of putrescible, plastic, paper and cardboard, textile, etc., that have been collected and dumped temporary at transfer stations, are from households, institutional and commercial centers of each local government area within the city, as presented in Fig. 2.

3.2. Data acquisition and preparation

3.2.1. Environmental criteria

3.2.1.1. Waterbody. To prevent waterbody pollution and contamination, this criterion is significant in siting WtE facilities as well as any hazardous disposal site. Hence, this data used was extracted from the latest land use land cover database of planet.osm [62]. It consisted of extracting and merging waterbody streams, reservoirs, rivers and lakes, into one data layer in polygon shapefile which has been converted through euclidean distance conversion toolbox into raster map (Fig. 3a), in natural breaks (Jenks) classification for suitability map analysis. Likewise, the raw polygon layer was used in the restriction map analysis.

3.2.1.2. Forest/agricultural area. The presence of agricultural activities areas mostly found in the outskirt of the city and some protected forest zones, are considered in this study as a criterion that influences solid waste generation, treatment and reuse processes in terms of technologies and site selection [46,48]. The dataset has been built from planet.osm database, by extracting and merging polygon shapefile into one layer which has been converted into raster map (Fig. 3b) in natural breaks (Jenks) classification through euclidean distance toolbox, for suitability map analysis.

3.2.2. Socio-cultural criteria

3.2.2.1. Sensitive area. Siting WtE facilities is a process which care about sensitive places mostly located in the urban areas of cities to avoid public opposition, environment and health risk hazardous. These areas in this study are composed of parks, zoo, education and institutional centers, airport, hospitals, recreational areas, religious houses, marketplaces, cemetery and other public areas as well as coastal area which was digitized from Google Earth. The others were extracted from planet.osm database, and merged into point and polygon shapefile, then converted into raster map (Fig. 3c) in natural breaks (Jenks) classification through euclidean distance conversion toolbox, for suitability map analysis. While, the raw layer was incorporated in the restriction map analysis.

3.2.2.2. Residence. Throughout any waste facilities siting, residence is one of the most critical criteria that influences the suitability sites analysis. From literature as well as ground experiences, residents have shown in many cases their opposition on the whole process of waste management sometimes due to bad feedback experiences. Indeed, it has been developed well-known syndromes around these issues such as NIMBY (Not In My Back Yard), NIMNBY (Not In My Neighbor Back Yard), NIABY (Not In Any Back Yard), BANANA (Build Absolutely Nothing Anywhere Near to Anyone) [55]. Therefore, the dataset used herein has been obtained from the public authority of DAGL in charge of waste management. The islets of residences were clustered in each of the 13th local government areas, and the layers in polygon shapefile were merged and converted into raster map (Fig. 3d) with natural breaks (Jenks) classification through euclidean distance processing under its toolbox, for suitability map analysis.

3.2.3. Economic/technical criteria

3.2.3.1. Slope. In this study, the slope plays an important economic or technical role as criterion that affects site suitability process regarding the risk of erosion, runoff rate, construction and operation plant, etc., as reported by Gorsevski et al., in landfill siting process. It has been derived from Digital Elevation Model (DEM) captured by Space Shuttle Radar Topography Mission (SRTM) at 1 arc-second (30 m) of spatial resolution from Earth Explorer (USGS). The slope raster (Fig. 3e) obtained from processing has a grid cell size of 30.84 m*30.84 m and was used as input layer for suitability map analysis, while the DEM was directly incorporated into restriction map analysis. The raster format of the overall processes in this study, was defined base on the DEM to keep results in same grid cell size.

3.2.3.2. Road network. The road network is fundamental for waste management route, its presence contributes to facilitate access of logistics to disposal sites, hence reduces significantly municipalities budget allocated to waste transportation from sources to final disposal sites. Therefore, the dataset used for analysis is extracted from planet.osm database and composed of main roads (i.e., primary, secondary, and tertiary roads) across the study area. One part of this dataset has been validated through the existing ground road

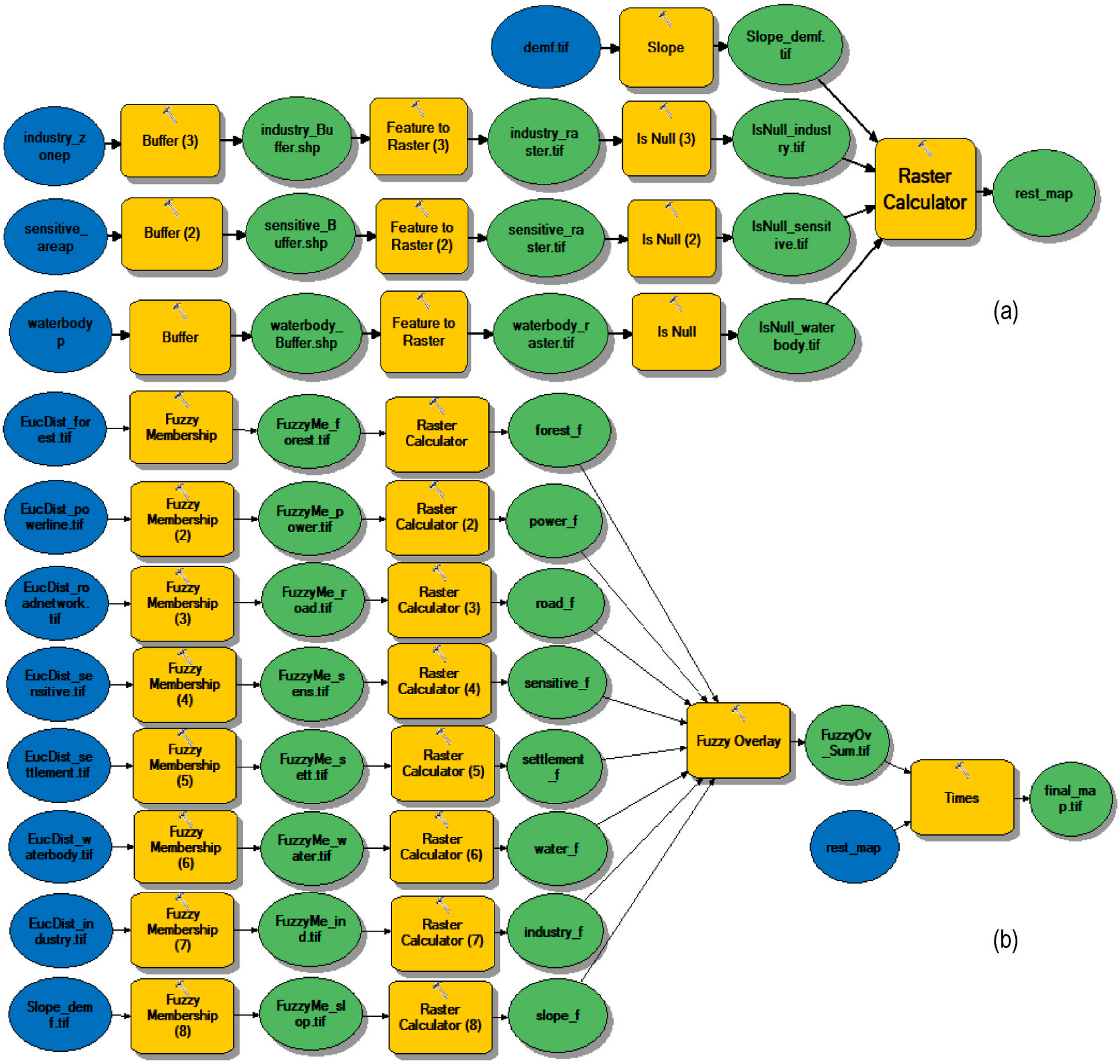


Fig. 4. (a) Computational modeling of restriction boolean map analysis (b) Computational modeling of FAHP of WtE facilities sites suitability map analysis.

network gathered from DAGL, that covers only the ancient local government areas of Lomé. For the purpose of this study, the new local government areas have been included with their road network from planet.osm. The data layer in polygon shapefile, was then converted into raster map (Fig. 3f) through euclidean distance toolbox in natural breaks (Jenks) classification and considered as input for suitability map analysis.

3.2.3.3. Powerline. For the purpose of energy recovery from solid waste and facilities operation, the siting process requires to take into consideration electricity distribution lines or poles so that the energy generated can supply customers. In this study, owing to the lack of powerline data, the main roads data is considered and assumed to be powerline data as it has been considered in siting anaerobic digestion plant in Oita city by Babalola [50]. The layer in polygon shapefile, is converted into raster map (Fig. 3g) through euclidean distance toolbox in natural breaks (Jenks) classification and considered for afterward suitability map analysis.

3.2.3.4. Industrial area. Based on the territorial aspect in siting WtE facilities, specifically in the technologies selection, industrial area is mostly suitable for pyrolysis or gasification process to be viable economically or technically [40]. So, the main industrial areas were digitized from Google Earth into polygon shapefile, and then used as input data layer for restriction map analysis. It is also used for suitability analysis, after been converted into raster data through euclidean distance toolbox in natural breaks (Jenks) classification (Fig. 3h).

3.3. Restriction analysis

As previously mentioned, four criteria have been considered (i.e., waterbody, sensitive area, industrial area, and slope) and were screened out of the study area. Indeed, siting WtE facilities requires to exclude certain areas and keep a minimum distance for safety purpose. Hence, the buffering areas of 100 m [48], are created around the criteria, and converted into raster layers through the function feature to raster and then into boolean raster with the function IsNull. These buffering areas are assigned to the value "0" and remain areas to the value "1" which respectively stand for not allowed and allowed areas. In addition, an exclusion zone from the DEM after been converted into slope layer, is defined to be areas with slope larger than 15% [63]. Ultimately, the toolbox raster calculator function was applied to combine layers with boolean informations contained in the rasters into the final restriction map under the environment of ModelBuilder in ArcGIS as shown in Fig. 4a.

3.4. Suitability analysis

In this section, the euclidean distance data layers and slope that have been prepared were used for reclassification through the fuzzy membership set into data layers with contents comprise between values "0" and "1". The MF used for this reclassification were based on sensitive control points which represent the threshold values of parameters from criteria considered in this study, and are shown in Table 1.

Once this step completed, the layers of each criterion were then weighted under the raster calculator toolbox, where the relative importance weight assigned have been defined through the PCM based on literature review as shown in Table 2.

The PCM is validated through the calculation of CR with regard of the relative importance weights, the matrix dimension and its eigenvalue. Once, the CR is obtained and acceptable, the average weights resulted were used to assign to criteria. They were incorporated in the raster calculator process, which overlayed criteria layers to get the suitability map considering the fuzzy sum operator as demonstrated in section 2. Therefore, the final suitability map is obtained by using simple multiplication of suitability and restriction maps which allows to screen out the restricted areas from the suitability map, as illustrated in Fig. 4b.

4. Results and discussion

Considering the geographical information specificities of the study area, siting WtE facilities have required to screen out the restricted areas defined through the criteria widely used as significant. These criteria such as waterbody, sensitive area, industrial area,

Table 1
Criteria standardization with fuzzy membership functions applied on control points.

Criteria		Initial control points (a and b)	**End control points (b and c)**	Fuzzy membership functions	References
Environmental	Waterbody	$a = 500$ m	$b = 2500$ m	Linear increasing	[28,47,64,48,68,]
	Forest/agriculture	$a = 250$ m	$b = 1200$ m	Linear increasing	[28,47,50]
Socio-cultural	Residence	$a = 500$ m	$b = 800$ m	Linear increasing	[28,47,51,65]
	Sensitive area	$a = 250$ m	$b = 1000$ m	Linear increasing	[28,47,64,65]
Economic/ technical	Road network	$b = 2000$ m	$c = 5000$ m	Linear decreasing	[28,64,65]
	Slope	$b = 10\%$	$c = 20\%$	Linear decreasing	[28,66,]
	Powerline	$b = 100$ m	$c = 1000$ m	Linear decreasing	[28,47,50]
	Industry	$b = 201$ m	$c = 2770$ m	Linear decreasing	[18,28,58]

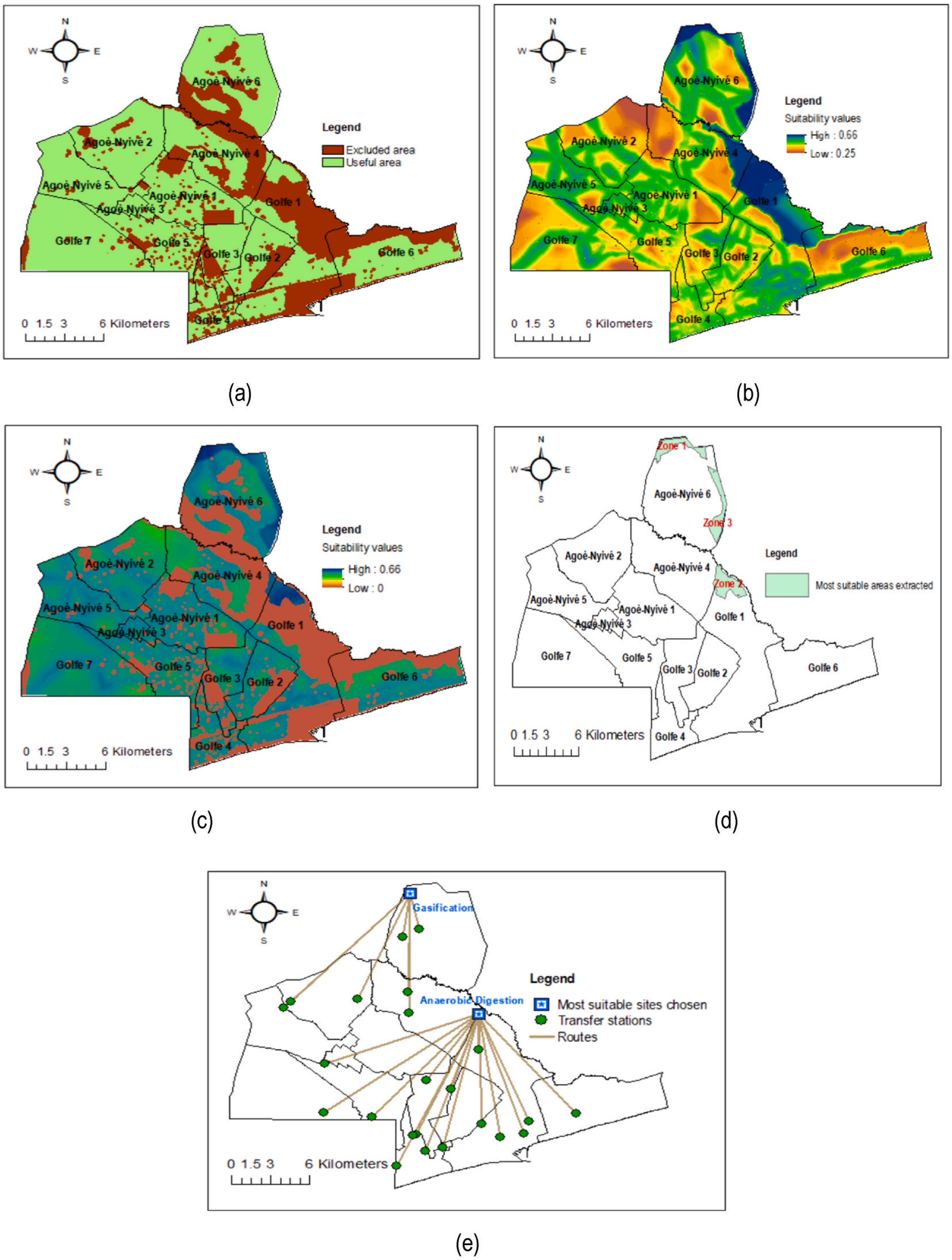
Table 2

Relative importance weight of criteria in the PCM.

Criteria	Residence	Slope	Powerline	Road network	Sensitive area	Waterbody	**Forest/agriculture**	Industry
Residence	1	1/2	1	2	8	6	5	3
Slope	2	1	3	3	4	6	6	6
Powerline	1	1/3	1	1/4	3	6	3	3
Road network	1/2	1/3	4	1	5	4	6	6
Sensitive area	1/8	1/4	1/3	1/5	1	1	1/3	1/4
Waterbody	1/6	1/6	1/6	1/4	1	1	2	1/2
Forest/agriculture	1/5	1/6	1/3	1/6	3	1/2	1	1
Industry	1/3	1/6	1/3	1/6	4	2	1	1

and slope were taken into account in the restriction modeling process, and about 130.7 km^2 was excluded which represents about 30.70% of the study area. Fig. 5a illustrates the excluded areas which have included environmental, socio-cultural, and economic/technical factors. The 69.30% of remain area, was dedicated for suitability siting analysis through the model built, thereby the FAHP was applied on all criteria chosen with their relative weights from PCM computed as shown in Table 3, with an acceptable CR equal to 0.09 inferior to the threshold value that is 0.1. This result demonstrates the consistency of the logic used by assigning relative weight to each criterion and prioritizing them in the pairwise comparison process. This value is similar to that found by Rafiee et al. [49], and slightly high than the value of Abdulhasan et al. [58], (i.e., CR = 0.083) in siting waste facilities.

In general, the aggregated weight of criteria has demonstrated the predominance of economic/technical and socio-cultural factors in the suitability analysis with respectively 68.30% and 23.19% of weight. Specifically, the slope and residence criteria with 29.13% and 19.84% of weight respectively, have influenced more the importance of their related factors in criteria evaluation. In fact, these values contribute significantly to reduce the final suitable sites areas, which was underlined in the study of Ferretti and Pomarico [65], in siting incinerator plant where the higher is socio-economic weight the lower is suitable sites areas. The lowest influencing criterion obtained is the sensitive area with 0.35% of weight under socio-cultural factor, meanwhile with 8.50% of weight the environmental factor appears to have the lowest importance in siting process. Thus, this result is confirmed by Wang et al. [67] in their study where the environmental and economic factors scored respectively the lowest and highest influencing weight in criteria evaluation. As a result, Fig. 5b presents therefore the suitability map obtained from the geoprocessing steps where the suitability values have been scaled continuously from 0 to 1, and increases with the values. This suitability map was then overlaid with the restriction map to obtain the final suitability map as shown in Fig. 5c. Three potential zones/sites were extracted and ranged between 0.57 and 0.66 of suitability values in this study, considering a minimum area of 3.47 km^2 and then validated on google earth and field visit as illustrated in Fig. 5d. Therefore, from sites 1 to 3 the suitability values decrease continuously and through a location-allocation analysis only sites 1 and 2 have been found to be most suitable considering the demand points and available road network within the study area for economic purpose as illustrated in Fig. 5e. The demand points are assigned to such optimal sites by minimizing road distance, through the straight lines herein representing the shortest routes to reach the facilities. This result confirms that sites 1 and 2 are the most suitable and shows the robustness of the modeling approach to improve and establish sound solid waste management as assumed. Moreover, the modelling approach flexibility to select more than one site has been demonstrated and could be explained by the influences of criteria on site alternatives. Consequently, the FAHP applied with the weighted overlay sum operator, has shown a comparable ability on site selection with the ordered weighted average method for landfill siting process applied by Gorsevski et al. [51]. Ultimately, the location-allocation has brought to the suitability analysis more effect of economic/technical factor on sites selected and justified the scale of the final suitability map. Furthermore, sites 1 and 2 are respectively located in the north and northeast of the study area outskirt with low density of residences. The presence of industrial area in the north and it proximity to site 1 has leaded the choice of gasification technology to implement there [40], while in the northeast the agricultural activity is closed to site 2 where the anaerobic digestion technology is recommended to implement [46,68]. These WtE technologies have proven by Afrane et al. [39], to be both the first best technologies to implement for energy production in Ghana as result of a MCDA on WtE technologies selection. Moreover, regarding the territory aspect and ranked suitable sites in this study the gasification technology appears ahead of anaerobic digestion, in contrast with a wide range of studies that have classified anaerobic digestion as the most suitable [34,36,38]. In addition, these results intend to minimize the cost of allocation of agricultural and industrial wastes in the study area and it suburbs, and was approved in the case study of bio-energy plant siting in Anambra State of Nigeria [31]. Meanwhile, the FAHP method used for standardizing criteria and comparing their relative importance weight, was able to successfully figure out the suitable sites which were optimized through a location-allocation analysis; within an allowable area of 0.81%–1.01% of the study area, and are approximately closed to the values (i.e., 1.0%–1.8%) found by Gorsevski et al. [51]. These proportions could highly decrease with the final sites obtained and comprise between 0.12% and 0.17% as generally found in the overlay and fuzzy logic method, according to Valizadeh [69]. Therefore, this study successfully achieves WtE facilities siting with regard to territorial aspect, transfer station locations, technologies specificities and waste sources under the new framework developed. However, the technologies criteria selections were not incorporated directly into the suitability model built due to the lack of experts and literature knowledge on technologies criteria definition to be included in a GIS processing of WtE facilities siting, based on the best of our knowledge. Moreover, the established model with its flexibility could incorporate more criteria and be extended to other given areas to significantly help the decision makers in the preliminary steps of WtE facilities siting in developing countries.



(a)

(b)

(c)

(d)

(e)

Fig. 5. (a) Restriction map (b) Suitability sites map (c) Final suitability sites map (d) Most potential areas extracted (e) Optimal sites and technologies selected.

5. Conclusion

Solid waste management system in developing urban areas has faced numerous challenges from waste sources to final disposal site involving environmental, socio-cultural, and economic/technical factors. Whereas, there is an opportunity for energy alternatives recovery and it urges to find ways to harness this potential for strengthening solid waste management and energy security. Therefore, siting WtE facilities alongside transfer stations considering territorial aspect, technologies specificities and solid waste sources of a

Table 3
Average weights assigned to criteria.

Criteria		Weight (%)	
Environmental	Waterbody	8.50	3.97
	Forest/agricultural		4.53
Socio-cultural	Residence	23.19	19.84
	Sensitive area		3.35
Economic/technical	Road network	68.30	19.99
	Slope		29.13
	Powerline		12.91
	Industry		6.27

given urban area, requires to take into account the crossover fields in decision making process of decision makers for sound and reliable waste management. This study has proposed a general modeling framework of WtE facilities siting with the aid of GIS tool where the FAHP and location-allocation were applied to figure out sites' suitability on the basis of MCDA method, on the territory of Lomé in Togo. The first step was to build a restriction model analysis with four criteria which has been able to exclude 30.70% of the study area for suitability analysis. The standardization of all criteria was applied through fuzzy membership linear functions and then the AHP was carried out for sites' suitability map analysis. It allowed to find three potential areas with a minimum value of 3.47 km^2 comprised between 0.81% and 1.01% of the study area, and with an acceptable CR of 0.09 from the PCM computed. The corresponding three potential sites chosen are highly influenced by slope and residence criteria from respectively economic/technical and socio-cultural factors. They were further used to optimize sites selection alongside transfer stations through the location-allocation processing which came out with two most suitable sites. Technologies types selection was based on the literature, and site close to industrial area in the north is assigned to gasifier while site located in the northeast close to agricultural activities is assigned to anaerobic digester. As a result, the gasification technology appears to be more important than the anaerobic digestion technology regarding the ranked sites suitability obtained in this study. These results have showed the robustness of the new modeling approach and have confirmed the assumption made on improving solid waste management through WtE facilities siting considering transfer station, territory aspect, waste sources as well as other criteria. Nonetheless, this modeling framework of WtE facilities siting could be extend using more criteria as well as technology criterion as direct inputs of the suitability analysis model built, to help decision makers for reliable and sound WtE technologies selection alongside sites suitability for sustainable waste management in developing urban areas. Otherwise, the overall approach of solid waste management should be implemented on the grassroot of good primary collection system and solid waste stream sorting for high performance of running WtE facilities to implement.

Author contribution statement

Kanlanféi Sambiani: conceived and designed the experiments; performed the experiments; analyzed and interpreted the data; contributed reagents, materials, analysis tools or data; wrote the paper.

Yendoubé Lare: conceived and designed the experiments; performed the experiments; analyzed and interpreted the data; contributed reagents, materials, analysis tools or data; wrote the paper.

Adamou Zanguina: analyzed and interpreted the data, wrote the paper.

Satyanarayana Narra: analyzed and interpreted the data, wrote the paper.

Data availability statement

Data will be made available on request.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships with other people or organizations that could inappropriately influence this paper.

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