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Combining multi-criteria decision analysis with GIS approaches for decentralized organic wastes composting plants site selection in Tiassalé, Southern Côte d'Ivoire

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Abstract

In recent years, decentralized composting appeared as one of the most appropriate treatment options for organic waste valorization in low- and middle-income countries. In Cote d'Ivoire, a pilot project has proved the feasibility of organic municipal solid waste composting for the city of Tiassalé. However, numerous issues still need to be addressed for the establishment of a sustainable decentralized composting system in this city. One of the key issues is site selection. Until now, there is no clear model for such plant site selection. In this study, multi-criteria decision analysis (MCDA) and geographical information system (GIS) approaches were combined to develop an appropriate model for selecting decentralized composting sites in the city of Tiassalé. The methodology used involved two different and complementary phases. First, MCDA and GIS techniques were used to identify the most suitable site areas. Seven criteria clustered in three main factors (environmental, social and economic), and five constraints were considered in the analysis process. Second, five sites were selected within the most suitable areas after a basic field visit and ranked using the Analytic Hierarchy Process. The results showed that the most suitable spaces for decentralized composting plant siting represent only 2.6% of the study area. The investigation yielded on the selection of the two best options for decentralized composting plant siting for the city of Tiassalé. This study proved that the combination of MCDA and GIS is a practical and efficient method to identify suitable sites for decentralized composting plants.

Keywords

Decentralized composting, GIS, MCDA, AHP, organic wastes, site selection

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Introduction

Urban centres in low- and middle-income countries are currently facing serious waste management problems (Getahun et al., 2012). This situation could worsen in the coming years as the World Bank predicts that waste generation in these countries will increase over 43% by 2030 (Kaza et al., 2018). Therefore, to cope with the increasing waste generation, there is a need for these countries to improve their waste management system towards integrating environment-friendly treatment methods, which additionally yield in products from waste.

In low- and middle-income countries, organic waste represents more than 50% of municipal solid waste streams (Bezama et al., 2007; Kaza et al., 2018). The high water content and proportion of easily degradable wastes render composting the most appropriate option for organic waste valorization (Thanh and Matsui, 2011). However, the majority of the centralized, large-scale composting plant projects in urban centres of low- and middle-income countries have failed (ADB, 2011: 459). These failures are attributed to several factors including high transportation, investment and operation costs, inappropriate technologies as well as low quality of the produced composts (Zurbrügg, 2004: 66). In recent years, there is a trend towards smaller, decentralized composting plants for these countries. In contrast to centralized composting plants

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which are highly mechanized and often located close to a dump site, decentralized composting plants are close to the cities, manually operated and their capacities rarely exceed 10 tonnes of waste per day (Drescher and Zurbrügg, 2006). Many initiatives of decentralized composting have been implemented in the last decade in countries such as India (Zurbrügg et al., 2004), Bangladesh (Zurbrügg et al., 2005) and South Africa (Friedrich and Trois, 2013). In Côte d'Ivoire, a pilot project in Tiassalé has proved the feasibility of organics municipal solid waste composting (Yeo et al., 2020). However, numerous issues still need to be addressed for the establishment of a sustainable decentralized composting system in this city. One of the key issues is site selection. In fact, inappropriate siting of a composting facility could endanger neighbouring populations and environment, and increase construction and operating costs (Babalola, 2018; Eskandari et al., 2015; Higgs, 2006). The identification and selection of suitable site for a decentralized composting plant is a complex task requiring the consideration of several economic, social and environmental factors. Given the numerous factors to be considered, the selection of a decentralized composting site appeared as a spatial multi-criteria decision analysis for which both geographical information system (GIS) and multi-criteria decision analysis (MCDA) methods should be used.

GIS has the advantage of gathering a set of geographic data like maps, aerial photographs and satellite images, analysing them and presenting the results on maps (Kallel et al., 2016). MCDA is a decision-making tool that combines stakeholder and expert opinion with factual information to solve decision-making problems utilizing a number of criteria (Geneletti, 2010; Stemn and Kumi-Boateng, 2019). Hence, the integration of GIS and MCDA could represent an appropriate and powerful problem-solving tool for addressing site selection issues.

The integration of GIS and MCDA tools (Analytic Hierarchical Process, Analytic Network Process, Weighted Linear Combination or Simple Additive Method) have been widely used in landfill, incineration and anaerobic digestion plants siting in the last years. For example, Stemn and Kumi-Boateng (2019) proposed a model based on MCDA–GIS approach for hazardous waste landfill sites selection in Western Ghana. The model used considered three major criteria (geo-environmental, social and economic) and 32 sub-criteria, which were weighted by AHP. Feyzi et al. (2019) performed a land suitability analysis for municipal solid waste (MSW) incineration power plant siting in Rasht County (Northern Iran). These authors considered three main criteria namely environmental, economic and sociocultural criteria and 15 sub-criteria. The decision-making trial and evaluation laboratory (DEMATEL) technique was used by these authors to identify the interrelations within criteria/sub-criteria. Then, fuzzy analytic network process (FANP) was used for criteria and sub-criteria weighting. Also, Babalola (2018) developed a case study on anaerobic digestion siting using a geographic information system based multi-criteria decision analysis (GIS-MCDA) in Oita City, Japan. The proposed model considered three constraints (environmental, sociocultural and technological/economic), and seven sub-criteria (water bodies, roads, powerlines, residential areas, forestry, tourist attraction areas and slope gradients).

Regarding composting plant site selection, limited works have been conducted using GIS-based-MCDA approaches (De Feo and De Gisi, 2010; Liu et al., 2018). Liu et al. (2018) developed multiple attribute decision making (MADM) based Analytic Network Process (ANP) to evaluate preselected sites for composting site selection in Miaoli county (Taiwan). De Feo and De Gisi (2010) have proposed a criteria weighting tool (CWT) for stakeholders involvement to rank centralized composting facility sites using the AHP in the Campania region (Italy). In the first phase of their study, these authors also developed a GIS-based-MCDA for extracting restricted areas.

However, until now there is no model focusing on finding out the best areas for composting plant siting using GIS-based-MCDA approaches. Moreover, no work is reported specifically on decentralized composting plant siting in urban centres of low- and middle-income countries. This study aimed at filling this gap by developing a GIS-based-MCDA model for selecting decentralized composting plant site in the city of Tiassalé (Côte d'Ivoire). To fulfil this goal, three specific objectives have been identified:

1. identify the most relevant constraints and criteria for decentralized composting site selection;
2. develop a GIS-based-MCDA model to identify the most suitable areas for decentralized composting plant siting; and
3. propose a method for suitable sites ranking using AHP technic.

The results of this study could help the municipal authorities of Tiassalé in the decision-making process for decentralized composting plants site selection. Moreover, this model could also be applied to other cities with similar characteristics.

Study area

Tiassalé is the second largest city of the Agnéby-Tiassa region in Southern Côte d'Ivoire. This city is located at about 125 km from Abidjan, the economical capital city. According to the 2014 national population and housing census, Tiassalé has 20,057 inhabitants (INS, 2015) living in 12 neighbourhoods. The city covers an area of about 6.6 km^2 and has a density of 3039 inhabitants per kilometre. This city is located in a forest region and is characterized by a tropical humid climate with a low ventilation. It is bordered in the east by the Bandama River, which is one of the main rivers of the country (N'krumah et al, 2017). The economic activities are dominated by agriculture with several large plantations of bananas, rubber trees and cocoa.

In secondary cities of Côte d'Ivoire like Tiassalé, waste management responsibility rely on municipal authorities with a very limited support from the central government. In Tiassalé, given the limited resources of the municipality, waste collection service

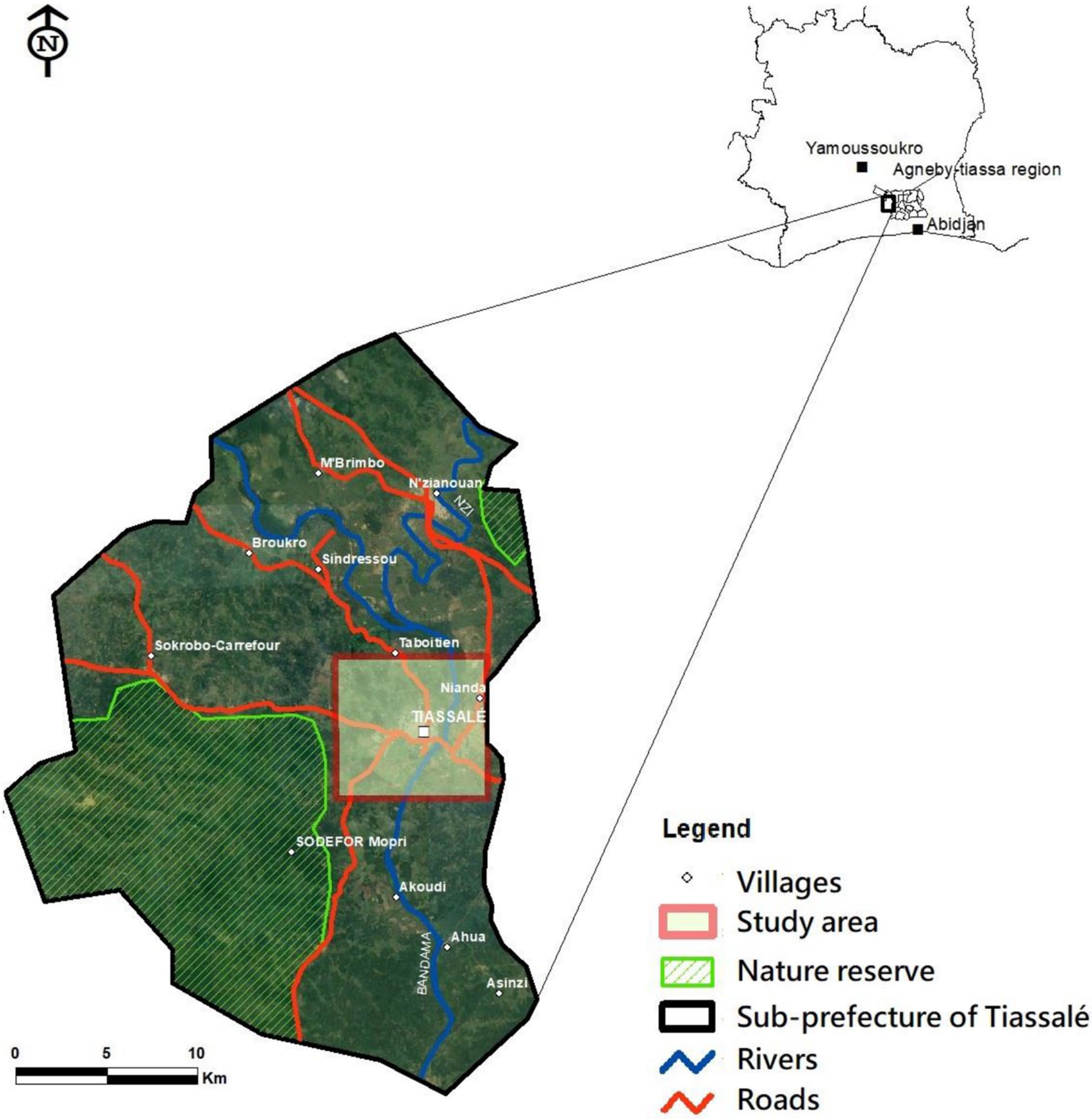

Figure 1. Map of Tiassale's sub-prefecture showing the study area.

covered only wealthier areas and the municipal market. This situation resulted in the increasing of open dumping sites. Currently, about 60 tonnes of waste are produced daily in this city with a proportion of more than 50% of organic waste (Yeo et al., 2020). The establishment of sustainable decentralized composting plants in this city could improve the current waste management system. The study area considered in this research includes the urban area of Tiassalé and its close vicinity of about 3 km around the city for a total of 64.6 km^2 (Figure 1).

Material and method

The methodological procedure of this study can be divided into two main phases. The first phase aimed at identifying the most suitable areas for decentralized composting plant siting. The procedure used in this phase included three steps: First, the identification and setting of constraints and criteria; second, the criteria comparison using the Analytic Hierarchy Process (AHP) pair-wise comparison method; and finally, the criteria and constraints maps were aggregated to generate the land suitability map. The different stages of data analysis of this first phase are illustrated in Figure 2. In the second phase, five sites within the most suitable areas were selected and ranked using AHP. The detailed descriptions of the procedure are presented in the next sections.

Constraints and criteria identification

The procedure used for constraints and criteria selection includes two phases. First, a list of constraints and criteria were selected

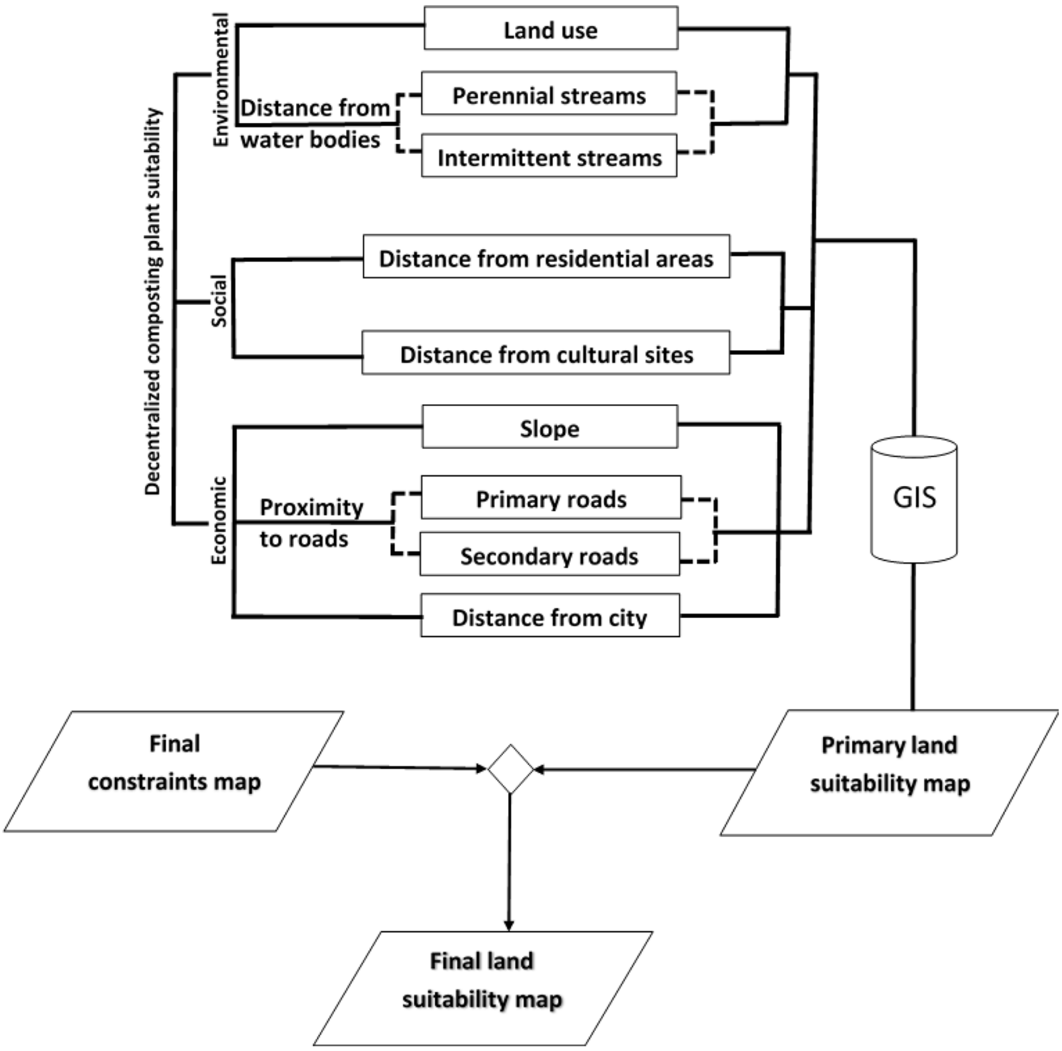

Figure 2. Flowchart of the first phase.

from literature regarding the study area characteristics and the available data. Then, these lists were reviewed by discussing with waste management experts to ensure their exhaustiveness and relevance. This reviewing process resulted in the selection of five constraints and seven criteria.

Constraints. The constraints represent areas that are prohibited for composting plant siting. The five constraints selected include residential areas, rivers, forests, wetlands and cemeteries. For each of these constraints, a binary map was developed with values of 0 given to the exclusionary areas and 1 affected to non-exclusionary areas.

Criteria. Criteria are a set of predefined characteristics used to describe objects that could influence the studied phenomena. The seven criteria selected in this study include land use, distance from water body, distance from residential areas, distance from cultural sites, proximity to roads, slope and distance from the city. The distance from a water body and the proximity to roads criteria were furthermore divided into two sub-criteria each: distance from perennial streams and distance from intermittent streams for the first, and proximity from primary roads and proximity from secondary roads for the second one. These criteria were then grouped according to their domain of influence into environmental, social and economic factors.

Environmental factors

Land use

Siting a decentralized composting plant requires to take into consideration the current land use to identify the available space. Given the lack of such data in the study area, a land use map was elaborated using a Google Earth imagery. This imagery interpretation was based on contact person's knowledge of the study area and field observations. The land use in the study area comprises 10 entities including cultural sites, forests, industry areas, irrigated rice fields, rubber plantations, rain fed farmlands, river, settlements areas, vacant land and wetlands (Figure 3).

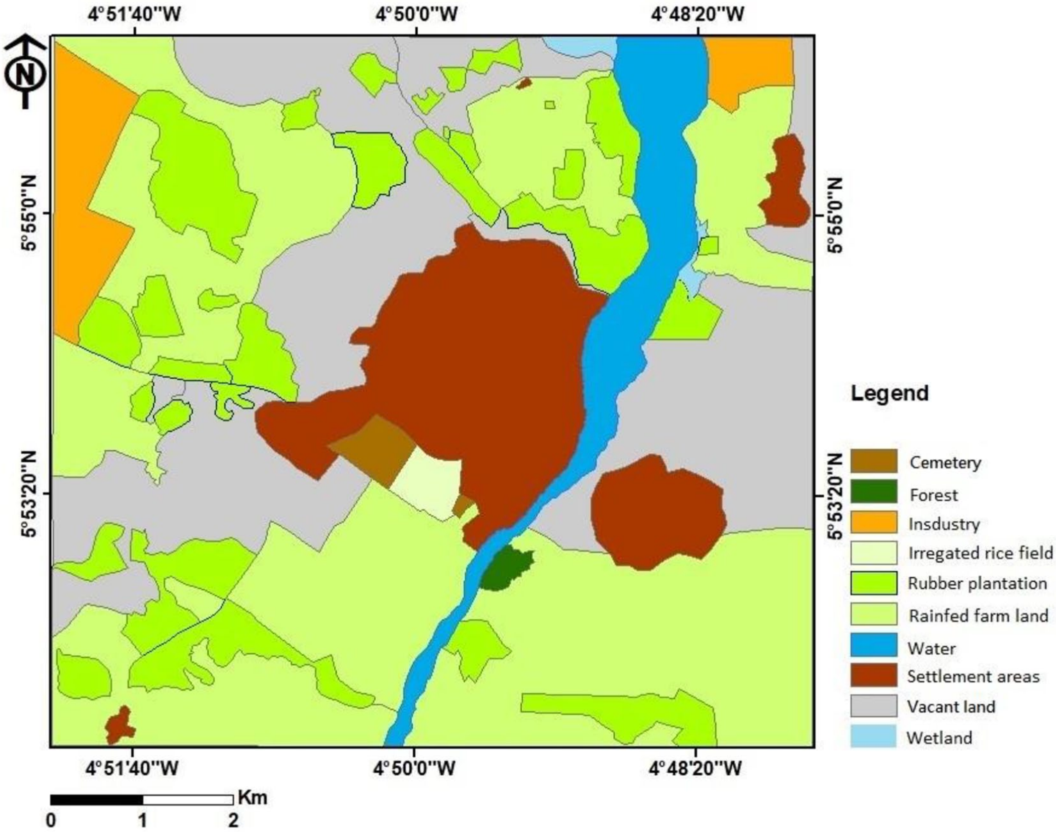

Figure 3. Existing land use.

Distance from water body

The decentralized composting plant under this study will be covered, with a solid underground and a leachate collection system. These characteristics reduce the risk of groundwater and surface water pollution. However, siting such plants near water bodies could result in river pollutions during flooding events. Hence, areas within 200 m from perennial streams and within 100 m from intermittent streams were considered as flood risk areas and therefore with low consideration for composting plants sitting (Babalola, 2018; Vasiljevic et al., 2012). During the classification and standardization step (described in the next section), the lowest weight was assigned to these areas while the highest weight was assigned to areas with distances more than 800 and 400 m from perennial and intermittent streams, respectively (Babalola, 2018; Gorsevski et al., 2012).

Social factors

Distance from residential areas

The main threat to population health related to the presence of a composting plant is the release of aerosols during the composting process (EA, 2010). These particles of about 10 µm consist of, for example, bacteria, fungi, pollen and cell fragments that could cause respiratory diseases when inhaled. To reduce these health risks, some countries have set a minimum distance between composting plants and residential areas. This distance ranges from 250 to 500 m in some European countries for open windrows composting (Douglas et al., 2016). In the absence of such regulations in Côte d'Ivoire, this study used 500 m as minimal distance to assign the lowest weight to the zone between 0 and 500 m and the highest weight to the area above 1000 m.

Distance from cultural sites

Several authors (Babalola, 2018; Geneletti, 2010; Vasiljevic et al., 2012) have underlined the need to locate waste treatment sites at a reasonable distance from cultural sites such as sacred forests, cemeteries and other historical sites to avoid the opposition of local communities. The cultural sites identified in the study area are the municipal and villagers' cemeteries in the town of Tiassalé. The lowest weight was assigned to areas within 250 m while areas located more than 500 m away received the highest rating.

Economic factors

Proximity to roads

The road network is an important criterion to consider when setting up a composting plant. Composting plants should be located

Table 1. Scale for pair-wise comparisons (Saaty, 1980).

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgement slightly favour one activity over another
5	Essential or strong importance	Experience and judgement strongly favour one activity over another
7	Demonstrated importance	An activity is strongly favoured, and its dominance is demonstrated in practice
9	Absolute importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between two adjacent judgements	When compromise is needed
Reciprocals of above nonzero	If activity 'i' has one of the above nonzero numbers assigned to it when compared with activity 'j', then 'j' has the reciprocal value when compared with 'i'	

near existing roads in order to avoid additional costs associated with the construction of access roads (Nas et al., 2010). Only primary and secondary roads were considered in this study, because these roads are in a good condition and fairly good under all weather conditions. Areas within 100 m from these roads received the highest score. Whereas areas located over 400 m away from existing roads were affected with the lowest score (Ghobadi et al., 2013).

Land slope

Slope influences both plant's construction costs and its accessibility to collection vehicles. In fact, the construction of a composting plant on a steeply site will result in significant levelling costs and it would be difficult to collection vehicles to reach the plant when loaded. Hence, areas with a slope of less than 10% received the highest score while those with a slope of more than 20% were affected with lowest score (Babalola, 2018).

Distance from city

The transportation cost is an important feature to consider when selecting waste treatment sites. Siting a waste treatment plant too far from the city (waste generation point) leads to an increase of fuel costs and, thus, reduces the cost-effectiveness of the plant. Hence, land suitability decreases when the distance to the city increases. This sub-criterion is thus in contrast with distance from residential areas sub-criterion, where suitability increases when the distance to the city increases (Javaheri et al., 2006). According to the expert's views, within 1000 m from the city received the highest score while areas located over 2000 m away from the city were affected with lowest score.

Classification and standardization of criteria and sub-criteria. For each criterion and sub-criterion, the study area was divided into different zones (classes) according to their suitability to composting plant siting. For example, when considering the slope criterion, the study area has been divided into three classes ($Ø < 10\%$; $10 < Ø < 20\%$; $20\% < Ø$). Based on these classes, criteria and sub-criteria maps were generated in a GIS software. Given the various scales on which criteria and sub-criteria were expressed, it was necessary to standardize these data to a common measurement scale in order to overlay the different map layers. Therefore, criteria and sub-criteria maps were converted into raster map of 30×30 m cell size and standardized. The constraints map was standardized using Boolean methods to limit their values to either 0 (exclusionary areas) or 1 (non-exclusionary areas). Criteria and sub-criteria maps were standardized using a grading method, with suitability values within 1–5, where 1 represents the lowest level of suitability and 5 represents the highest level of suitability for decentralized composting plant siting. The classification and standardization used in this study were based on comparable studies (Ghobadi et al., 2013; Karakuş et al., 2019; Vasiljevic et al., 2012) and the local expert's views.

Factors, criteria and sub-criteria weighting. Factors, criteria and sub-criteria were weighted using AHP method (Saaty, 1980), which is based on the pair-wise comparison of the importance of the different elements. The first step of this weighting process was the structurization of the factors, criteria and sub-criteria hierarchically. In the second step, pair-wise comparison matrices were established for each level of the hierarchy. These matrices were sent to 15 experts (10 researchers from national universities and five practitioners in solid waste management and GIS fields) who performed the pair-wise comparison using a relational scale of real numbers from 1 to 9. The value 1 represents equal importance, while the value 9 refers to the most important (Table 1). In the third step, the expert judgements (scores) for each matrix were imported into *Expert Choice* software, and the final weight of each factor, criterion and sub-criteria as well as the consistency ratio (CR) of the different matrices were obtained. The CR measures the level of inconsistency of the pair-wise comparison matrix. When this ratio (CR) is less than 0.1, the judgements are considered as consistent, and the derived weights can be used. In contrary if CR is higher than 0.1 the judgements should be reviewed.

Criteria, constraints, aggregation and land suitability map conception. After criteria weight determination, these values were used to aggregate the environmental, economic, and social criteria standardized maps to obtain the environmental, economic and social factors maps, respectively. These intermediates maps were then aggregated again to generate a single map depicting land suitability to composting plant sitting (primary suitability map). In both cases, the aggregation was performed using the weight linear combination (WLC) method. The WLC aggregation technique is the sum of the product of each standardized criterion map and the criterion weights (equation 1) (Eastman, 2006).

$$S = \sum_{i=1}^{n} WiXi \tag{1}$$

where:

S: land suitability index; Xi: standardized raster layers; and Wi: layer's weight.

In the same way, all the constraints maps have been combined to generate the final constraint map according to equation (2).

$$S = \prod_{j=1}^{n} C_j \tag{2}$$

where:

S: suitability index (1, 0) and C_j: suitability index of constraint j.

The primary suitability map obtained, was combined to final constraint map based on equation (3) below to obtain the final land suitability map for composting plant siting. The purpose was to exclude areas within the exclusionary areas that might have been classified as suitable for composting plant siting.

$$S = \sum_{i=1}^{n} WiXi \times \prod_{j=1}^{n} C_j \tag{3}$$

where:

S: land suitability index and Π: product sign for the constraints, meaning that the product of constraints is multiplied by the summation of $WiXi$.

Sites selection and ranking. The second phase of this study started by a basic ground check within the most suitable areas identified in the first phase. In each of these areas, a site was selected using three criteria including landscape, absence of heavy plants or outcrop and proximity to existing road. Then these sites were ranked using AHP method again. For this purpose, a second set of three criteria was selected to evaluate and rank these sites. These criteria were identified through discussion with the 15 experts consulted in the first phase. The selected criteria included water availability, accessibility and land cost (Table 2).

Table 2. Criteria adopted for sites evaluation.

No.	Criteria	Criteria evaluation
1	Water availability	Surrounding well water table depth Soil type which influences well digging cost and water Water availability in dry season
2	Accessibility	Distance from the city centre Roads quality under all weather conditions Distance from existing roads
3	Land cost	Surrounding land cost

The analysis of this second phase encompassed three steps:

1. The pair-wise comparison of these criteria was performed by the same 15 experts consulted in the first phase.
2. Site evaluation was done through interviews with 10 resource persons (including five local authorities) familiar with local conditions.
3. Finally, the stability of the sites ranking obtained was assessed through sensitivity analysis.

All the analyses were carried out using 'Expert choice' software.

Results and discussion

First phase: Land suitability assessment

Weight of factors and criteria. Based on the expert's views, the result showed that the environmental factors were the most important (0.55), followed by the social factors (0.25), and the economic factors were the less important (0.21), as shown in Table 3. For all the comparison matrix, the CR was below 0.1, which indicates that the judgement made by experts were suitable. The higher preference given to environmental criteria is certainly due to the importance for experts to protect the Bandama River which is used for extracting drinking water for Tiassalé and the neighbouring cities. Previous studies conducted by Eskandari et al. (2015) and Vasiljević et al. (2012) have identified environmental criteria as the most important in landfill site selection, thus confirming the relevance of this criteria in any site selection for waste treatment purposes.

Based on the class and rating scores of Table 3, the standardized maps generated for seven criteria are presented in Figure 4. Distance from water bodies (b) and distance from roads criteria (g) were divided into two sub-criteria.

The rate 5 (in purple) represents the most suitable areas for each criterion while rate 1 (in green) represents the less suitable

Table 3. Criteria and sub-criteria weight with rating values of sub-criteria classes.

Factors	Weight	CR	Criteria	Weight	CR	Class	Rating
Environmental	0.55	0.02	Land use	0.33	0.00	Cultural sites	1
						Settlement areas	1
						River	1
						Industry	1
						Irrigated rice field	1
						Wetland	1
						Rubber plantation	2
						Rain fed farmland	3
						Vacant land	5
			Distance from water body (m)	0.67			
			• Perennial stream	0.45		<200 m	1
						200–400 m	2
						400–600 m	3
						600–800 m	4
						>800 m	5
			• Intermittent streams	0.22		<100 m	1
						100–200 m	3
						200–400 m	4
						>400 m	5
Economic	0.21	0.02	Slope (%)	0.24	0.02	<10%	5
						10–20%	2
						>20%	1
			Distance from roads (m)	0.55			
			• Primary roads	0.37		<100 m	5
						100–200 m	3
						200–400 m	2
						>400 m	1
			• Secondary roads	0.18		<100 m	5
						100–200 m	3
						200–400 m	2
						>400 m	1
			Distance from city (m)	0.21		<1000 m	5
						1000–2000 m	3
						>2000 m	1
Social	0.24	0.00	Distance from residential areas (m)	0.75	0.00	<500 m	1
						500–1000 m	4
						>1000 m	5
			Distance from cultural sites (m)	0.25		<250 m	1
						250–500 m	3
						>500 m	5

areas; the other rates represent intermediate expression of suitability:

- Regarding land use, vacant land represents the most suitable areas for decentralized composting plant siting.
- Concerning distance from water body criteria, the areas located at a distance of more than 800 and 400 m from perennial and intermittent streams, respectively represent the most suitable areas.
- Areas with a slope of less than 10% were considered as the most suitable.
- For distance from city, areas within 1000 m from the city were considered as the most suitable.
- Concerning distance from roads, areas within 100 m from existing roads were considered as the most suitable.
- Regarding distance from residential areas, those above 1000 m from the city were the most suitable.

The visualization of the situation obtained from the aggregation of these criteria maps is found in the primary land suitability map (Figure 5).

The suitability index of this primary land suitability map varies from 1.82 to 4.87. Figure 6 presents the final constraint map in which, exclusionary areas represent unsuitable areas for composting plant siting. These areas represent 21.49% of the study area.

Overall land suitability map. The overall land suitability map derived from the aggregation of the primary land suitability and constraints maps is presented in Figure 7. The exclusion of restricted areas was done at the end of the process rather than the

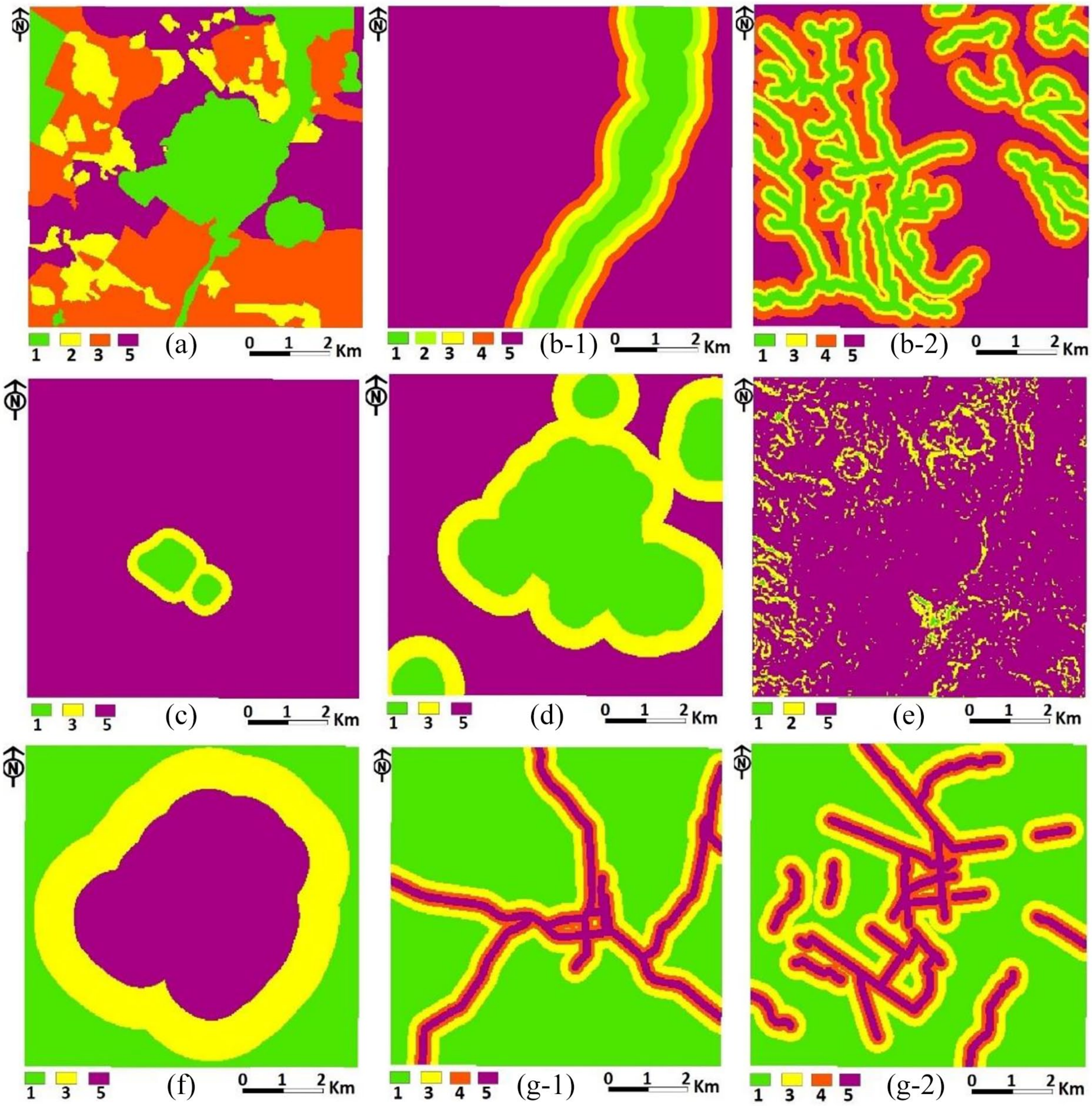

Figure 4. Criteria and sub-criteria standardized maps: (a) land use, distance from water bodies ((b-1) perennial stream, (b-2) intermittent stream), (c) distance from cultural sites, (d) distance from residential areas, (e) slope, (f) distance from city, and distance from roads, ((g-1) primary roads, (g-2) secondary roads).

beginning as recommended by Vasiljević et al. (2012). According to this author this approach is more accurate to avoid the omission of certain constraints areas. The land suitability index values obtained vary from 0.0 to 4.8, the minimum and maximum values, respectively. In order to best demarcate the most suitable areas for decentralized composting plant siting, this interval was classified into ten categories ranging from unsuitable (0) to very, very high suitability (4.8) using the natural breaks method (Jenks and Caspall, 1971) (Table 4). This method has the advantage of minimizing the variance within classes and maximizing it between classes (Mohebbi Tafreshi et al., 2018) and has already been used in similar studies (Basnet et al., 2001; Gbanie et al., 2013; Shoba and Rasappan, 2013).

This final map (Figure 4) shows that 21.7% of the study area is unsuitable for decentralized composting plant siting while only 2.6% is ranked in the class 'very, very high' suitable for decentralized composting plant siting. As it can be seen from Figure 4, the most suitable places (class: 'very, very high') for decentralized composting plant siting are patches of land located mainly in the North, the Southwest and East of the study area. These areas are located in vacant land and at more than 500 m from residential areas. Moreover, these sites are sufficiently far from water bodies. These results demonstrate that the model implemented in this study is effective for the identification of the most suitable areas for decentralized composting plant siting.

The approach implemented in this study is an advancement over the model developed by De Feo and De Gisi (2010). In contrary of these authors' model which is designed for extracted restricted areas, the model developed in this study focuses on

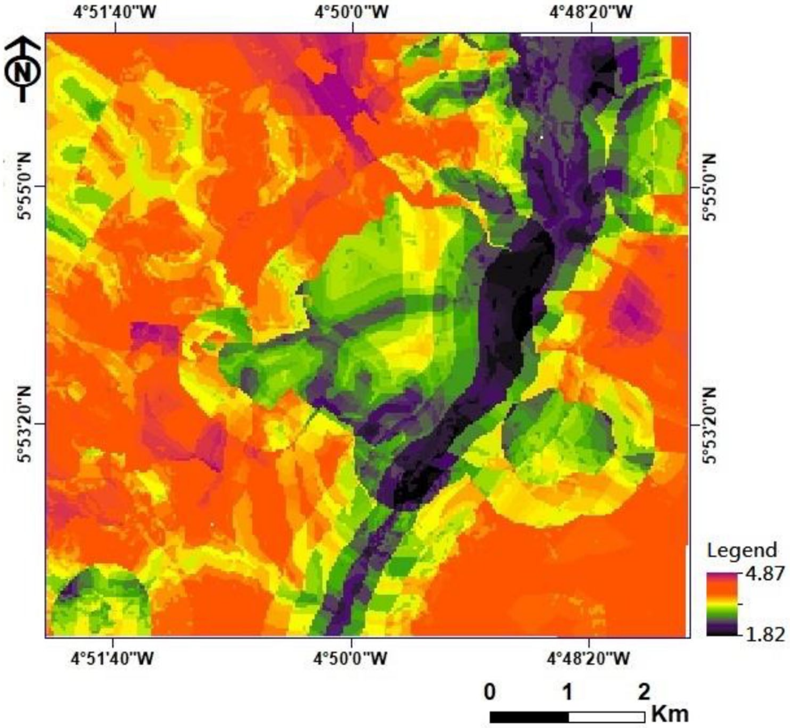

Figure 5. Primary land suitability map for decentralized composting plant siting.

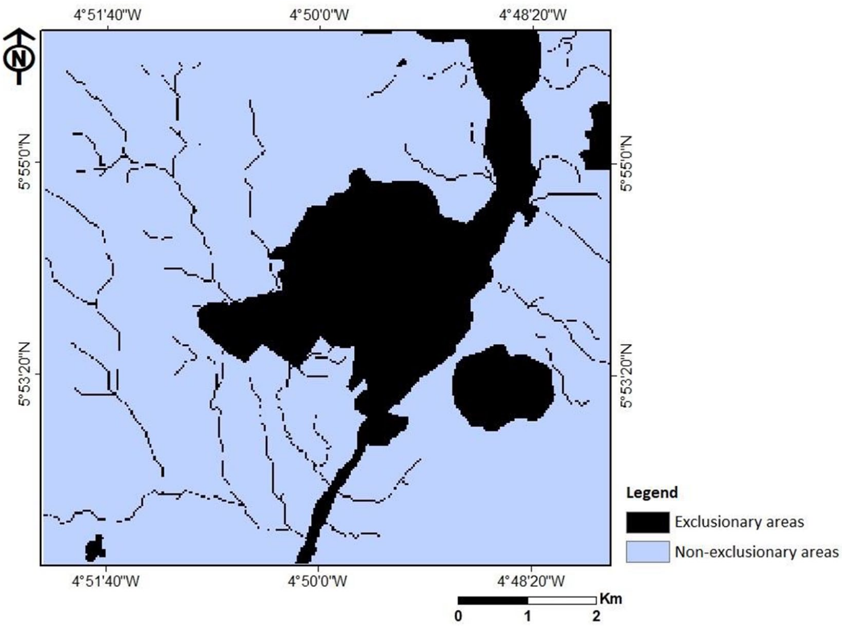

Figure 6. Final constraints map for decentralized composting plant site selection.

finding the most suitable areas for composting plant siting. Very often, the high number of criteria considered in site selection model limits their applicability in low- and middle-incomes countries because of the absence of required data. Another advantage of this study is the fact that our model is based on constraints and criteria which data are easily accessible in low- and middle-incomes countries' context. These advantages render our model suitable for the urban centres of these specific countries.

Alternative sites

The five alternative sites selected in the most suitable areas are presented in Figure 8. All these sites are located at more than

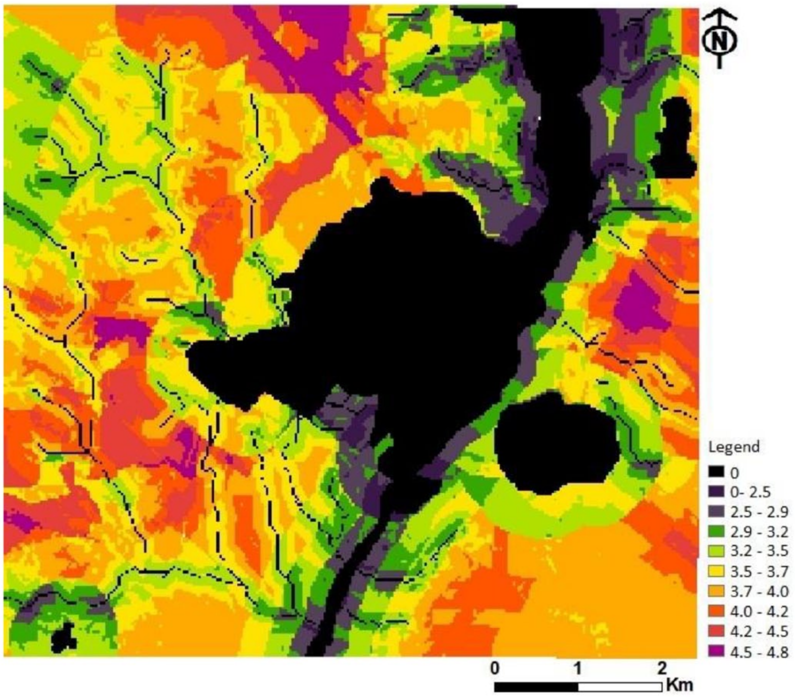

Figure 7. Tiassalé land suitability map to decentralized composting plant siting.

Table 4. Land suitability index classes, with the corresponding surface area.

Class	Index	Area (m^2)	Percentage of total area (%)
0	Unsuitable	14,042,132	21.7
0–2.5	Very, very low	1,267,559	2.0
2.5–2.9	Very low	3,501,884	5.4
2.9–3.2	Moderately low	4,253,386	6.6
3.2–3.5	Low	8,115,645	12.5
3.5–3.7	High	9,259,235	14.3
3.7–4.0	Moderately high	12,599,671	19.5
4.0–4.2	Moderately very high	6,192,684	9.6
4.2–4.5	Very high	3,767,120	5.8
4.5–4.8	Very, very high	1,674,062	2.6
Total		64,673,378	100

500 m from city and on flat plots of unused areas. In addition, except site 4, all the other sites are located at less than 100 m from a main road.

Given the fact that these sites have very similar land suitability index (phase 1), three additional criteria were selected to differentiate the performance of these sites. In contrast to the criteria selected in the first phase, the second phase criteria can only be evaluated for the selected sites, rather than be generally for the whole study area. Comparatively to previous sites evaluation and ranking studies (De Feo and De Gisi, 2010; Liu et al., 2018), the number of criteria used in this second phase was very low. This result is due to two phases approach used in this research as the first phase already permitted to optimize the selection process.

Table 5 shows the result of the pairwise comparison of the three criteria with the weights assigned to each criterion. This result shows that the most important criterion was water availability (0.47), follow by accessibility (0.43) and land cost (0.1). The primacy given to the water availability criterion is motivated by the high water requirements of composting units in such climatic areas (Yeo et al., 2020). While, the minor importance given to the land cost, indicates that for the experts, when a site meets water availability and accessibility criteria requirements, land cost should not be an obstacle to the selection of that site.

The results of sites comparison showed that sites 4 and 5 had the lowest land price, while site 1 had the highest land price. In term of accessibility, sites 2 and 3 were the most favourably located, because, these sites are the closest to the city centre on one hand and on the other hand, access roads to these sites are in a very good state. Concerning water availability, site 3 was the most favourable due to the low water table depth in this area (Ø < 3 m) and the soil type (sandy–clay soil) which is easier to

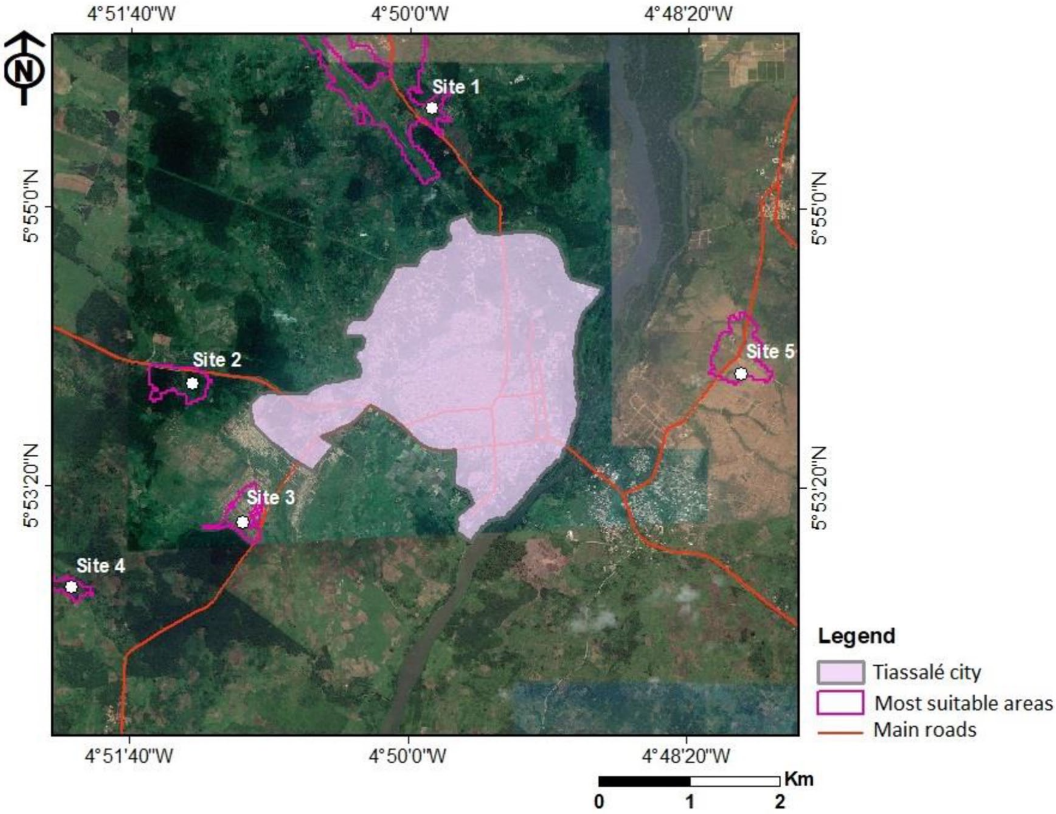

Figure 8. Location of the five selected alternative sites for decentralized composting plant siting.

Table 5. Pair-wise comparison matrix of criteria.

Second evaluation criteria	Land cost	Accessibility	Water availability	Weight
Land cost	1	–	–	0.1
Accessibility	4	1	–	0.43
Water availability	5	1	1	0.47

CR = 0.005.

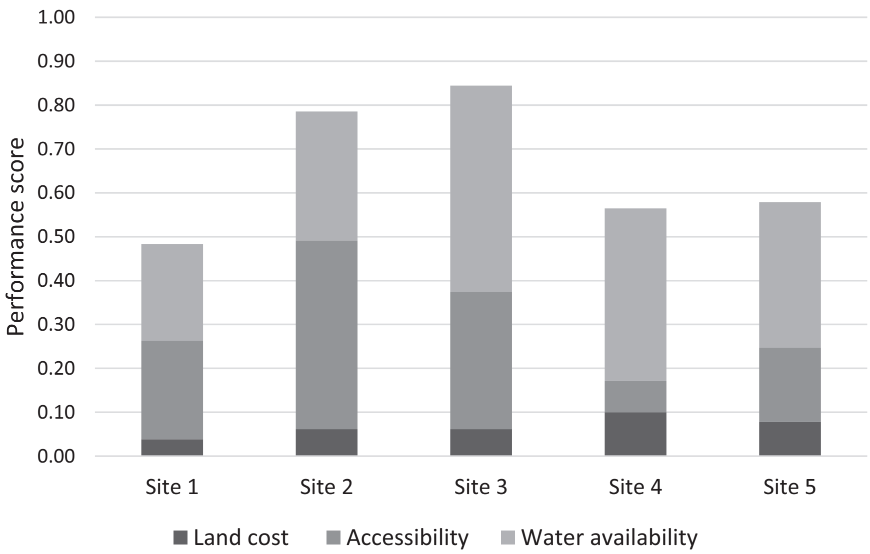

Figure 9. Ranking of the sites with indication of the relative contribution of the three criteria.

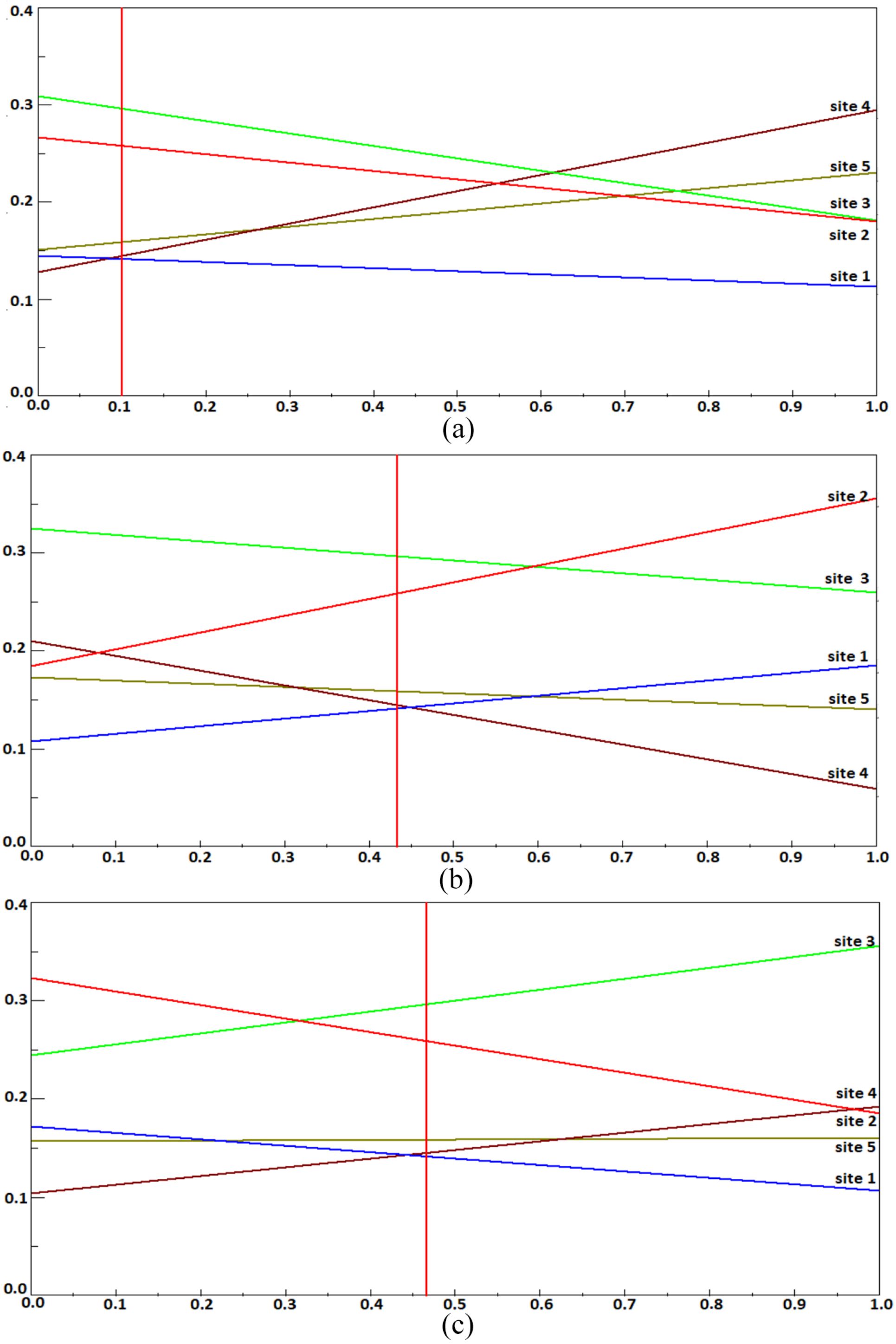

Figure 10. Sensitivity of the site ranking with respect to changes in the weight assigned to land cost (a), accessibility (b) and water availability (c).

dig. Whereas site 1 was the most disadvantageous given the difficulty to get sufficient quantity of water in this area during the dry season and the high digging cost of this area. Figure 9 illustrates the overall performance of each site with the relative contribution of each of the three criteria. Sites 3 and 2 ranked at the top, and sites 1, 4 and 5 at the bottom.

Sensitivity analysis of the obtained site ranking is presented in Figure 10. As it can be seen, the nearest reversal points where there is a change in the top (between site 3 and site 2's ranking) for all the three criteria occur at more than ±30% from the original weights. This result proved that the top part of the ranking is stable (Eskandari et al., 2015). Hence sites 3 and 2 are the preferred location for decentralized composting plant siting.

Conclusion

The selection of optimal site is a very crucial step when setting up a decentralized composting plant. In this study, we developed a

GIS-based-MCDA model for decentralized composting plant siting, taking the city of Tiassalé as a case study. The proposed model involved two phases. In the first phase, five constraints were selected to extracted restricted areas. Then seven criteria including land use, distance from water body, distance from residential areas, distance from cultural sites, proximity to roads, land slope and distance from city were selected and grouped into three main factors (environmental, economic and social) to identify the most appropriate areas for decentralized composting plant siting. In the second phase, five sites were chosen within the most appropriate areas previously identified after a basic ground check. These sites were then ranked using three other criteria which are: water availability, accessibility and land cost. The results of the first phase revealed that only 2.6% of the study area is suitable for composting plant siting. The second phase showed that sites 3 and 2 were the best options for decentralized composting plant siting. These sites generally satisfy the minimum requirements for decentralized composting plant siting. Nevertheless, a detailed field studies including detailed flood risk assessment, land ownership and questionnaire investigations to determine public acceptance of construction composting plant should be performed before choosing the final site. The findings of this study showed that the combination of MCDA and GIS techniques is an effective approach for decentralized composting plants sites selection. Moreover, the model implemented in this study is based on criteria which data are easily accessible in developing countries context. Therefore, this model can be used by waste management engineers and technicians in decentralized composting plant site selection process.

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