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A Two-Stage Based Life Cycle and Principal Component Analysis for Decision Support of Potential Municipal Solid Wastes Management Scenarios, Case study Dar es Salaam, Tanzania

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ABSTRACT

In most of the urban areas of Tanzania, poor and inadequate solid waste management is a growing environmental and public health concern. Despite an array of solid waste management options, choosing an appropriate one remains a challenge. This study applied a novel two-stage-based approach to assess the environmental impacts and sustainability performance of the 27 scenarios for municipal solid wastes (MSW) management of Dar es Salaam City, Tanzania. In the first stage, the study utilized a life cycle analysis (LCA) to quantify the environmental impacts of MSW scenarios. In the second stage, the study used the principal component analysis (PCA) to assess the sustainability performance of the same. The LCA results indicated that no scenario performed better in all environmental impacts. The current SWM option, which involves landfilling most of the wastes at the Pugu landfill, leads to adverse environmental impacts and therefore poses an environmental and public health risks potential. The PCA results indicated that the scenario that involves the composting of organic wastes, recycling of the recyclable materials and landfilling the rest of the waste is the more sustainable option with a score of -1.7105. Based on the sensitivity analysis, the transportation process is responsible for the higher environmental burdens in most scenarios. Thus, promoting resource recovery at the premises of the waste generation would be crucial for minimizing the environmental impacts. This study demonstrated that the decision-makers could potentially use a combined LCA-PCA methodology to select the optimal MSW scenario.

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INTRODUCTION

In most cities in developing countries, municipal solid waste management (MSWM) remains challenging and requires public attention. The current MSWM practices involve the crude dumping of wastes into the environment and therefore pose a threat to the environment and lead to food contaminations, the spread of infectious diseases, and contribution to climate change (Olabode and Lawrence, 2014; Dladla, Machete and Shale, 2016; Richard et al., 2019). To operate effective and efficient MSW management, requires, among others integrated solid waste management (ISWM) in the order of priority i) waste reduction, ii) recycling, iii) waste processing iv) waste transformation and v) landfilling (Palanivel and Sulaiman, 2014; Van Ewijk and Stegemann, 2016). In contrast, ISWM in most cities of developing countries is hardly practiced. The selection of the MSWM option is solely based on the experience and knowledge of the decision-makers (De Medina-Salas et al., 2017). Consequently, the selected MSWM option became ineffective because the selection could not consider the sustainability indicators in the assessment (Guerrero, Maas and Hogland, 2013; Sukholthaman and Shirahada, 2015; Mmereki, Baldwin and Li, 2016; Bundhoo, 2018). The assessment should cover the sustainability indicators including economic, environmental, and social dimensions. Furthermore, selection should consider the whole solid waste service chain, including collection, transportation, treatment, recovery and final disposal.

Various multi-criteria decision analyses (MCDA) have been employed to inform alternative scenarios. However, they have the disadvantage of deciding at the expense of losing important information (Wang et al., 2019). Recently, the MCDA approach using life cycle assessment (LCA) and principal component analysis (PCA) is increasingly receiving attention in the decision-making process for environmental impacts and sustainability assessment of waste management scenarios. LCA tool has been applied to analyze and compare the global environmental impacts of MSW options. However, different LCA results were obtained because of reasons such as system boundaries and waste compositions, whether or not to include equipment that causes emissions (Pires, Chang and Martinho, 2011). Therefore, results are study-specific. In some studies, LCA results were inconclusive. For instance, Tunesi and Rydin (2009) did not find the best way to manage municipal solid waste (MSW), even after a systematic follow-up of ISO 14040 standards to minimize the discrepancies in the criteria. In another study, Richard et al. (2021) found the LCA methodology to be the very tool to assess the best combination of scenarios for managing MSW of Arusha City, Tanzania. The results indicated three combinations of recycling, composting, and the landfill was the best scenario. However, the deciding factor was considered to be the operating cost of the scenario. This was decided since no scenarios performed better in all environmental categories assessed.

On the other hand, PCA is an effective data analysis tool for reducing and interpreting multivariate data sets by transforming a large set of variables into a smaller one without losing essential information. The strength of the PCA method lies in its capabilities of dealing with high correlation, where through the process, the correlated variables are reduced to a few principal components (PCs) that are not correlated and which describe the information of the original variables as much as possible (Jolliffe, Cadima and Cadima, 2016). Because of the smaller data sets, PCA allows better visualization of alternatives' pros and cons. One of the shortcomings in most multi-criteria analyses is the lack of a single score that could inform the conclusion. The Principal component analysis can address these challenges since the method generates scores of alternatives that aid in concluding the suitable options. Helness *et al.*, (2019) used PCA to assess the sustainability of seven integrated water strategies in Oslo City. The study obtained a score of 2.712 for the combination of measures of population growth, increased industrial water consumption and ageing infrastructure. This score was the lowest and was applied to decide the sustainable alternative action compared to other measure combinations with higher scores. Park, Egilmez and Kucukvar (2015) used the life cycle and PCA methodologies to quantify the environmental impacts and to assess the sustainability of the US manufacturing and transportation industries. The combined LCA-PCA results indicated that iron and steel mills manufacturing and agricultural chemical manufacturing were the more sustainable, with the lowest eco-efficiency scores of 0. 130. Therefore it is possible to combine results from other MCDA and Principal components to assist in reaching conclusions. Despite these studies, the application of different MCDA approaches, such as life cycle analysis and principal components to the MSW field has not been adequately and comprehensively studied and thus is not known and documented. In this regard, this study applies an innovative two-stage approach of LCA and PCA to aid the selection of the best MSW scenarios in Dar es Salaam City Tanzania.

METHODS AND MATERIALS

Life cycle - Principal component analysis approach

The study applied a two-stage approach consisting of LCA and PCA to assess the environmental impacts and more sustainable sustainability of municipal solid waste management scenario in Tanzania, using the municipal solid wastes generated in the Dar es City of Tanzania. PCA is developed to assess the sustainability of 27 scenarios obtained from Life cycle analysis. Therefore, in the first phase, Life cycle analysis is utilized to analyze the environmental impacts of the scenarios. In the second phase, LCA results are integrated into PCA, which computes the scores and loading of each scenario. As a result, the scenario with a low score is deemed to be more sustainable. The details of the proposed methodology are summarized in the section below.

Life cycle analysis

In this study, LCA compared different solid waste management scenarios according to ISO 14040 (ISO14040, 2006). The LCA approach comprises four main stages including goal and scope definition, life cycle inventory, life cycle analysis and interpretation of the results. The ReCiPe 2008 Midpoint (H). V1.13 methods (ecoinvent version 3.6) integrated with Umberto LCA software were used to compute the results.

Goal and Scope Definition

This study aimed to apply the LCA methodology to analyze the impacts of MSW management in Dar es Salaam City. Then *'end of life stage and zero burden assumptions'* were applied, suggesting that materials become wastes when their values cease and the waste carries none of the upstream environmental burdens. The daily solid waste generation in the city is approximately 9,000 metric tons and comprises 44.5% organic, 9% glass, 0.5% metals, 12% Papers, 22% Plastics, 5% textiles and 7% others (DCME, UDSM, 2018). The functional unit considered to analyze the alternative scenarios is based on a daily waste generation of 9,000 metric tons. Table 1 depicts the summary of the 27 MSWM scenarios studied.

Table 1: Description of the considered scenarios for the Life Cycle Assessment

Scenario	Description
S_1	10% Recycled (5.06% plastics, 2.76% papers, 2.07% glass, 0.11% metals) + 90% Landfilling (44.5% organic, 16.94% plastics, 9.24% papers, 6.93% glass, 0.39% metals, 5% t extiles, 7% others)
S_2	10% Recycled (5.06% plastics, 2.76% papers, 2.07% glass, 0.11% metals) + 44.5% composting (44.5% organic) + % 45.5 (Landfilling (16.94% plastics, 9.24%

	papers, 6.93% glass, 0.39% metals, 5% textiles, 7% others)
S_3	10% Recycled (5.06% plastics, 2.76% papers, 2.07% glass, 0.11% metals) + 44.5% Anaerobic Digestion (44.5% organic) + % 45.5 (Landfilling (16.94% plastics, 9.24% papers, 6.93% glass, 0.39% metals, 5% textiles, 7% others)
S_1_(RR), S_2_(RR), S_3_(RR)	The scenarios assumed the inclusion of avoided resource recovery (RR) environment burdens due to the production of electricity (hydropower) and mineral fertilizer (Nitrogen and Phosphorus) on S_1, S_2, and S_3, respectively.
S_1_(TR), S_2_(TR), S_3_(TR)	The scenarios assumed an increase of 5% improvement in transportation (TR) of wastes on S_1, S_2, and S_3, respectively.
S_1_(EL), S_2_(EL), S_3_(EL)	The scenarios assumed a 5% improvement in reducing electricity consumption (EL) on S_1, S_2, and S_3, respectively.
S_1_(CH_4), S_2_(CH_4), S_3_(CH_4)	The scenarios assumed a 5% improvement in reducing methane emission (CH_4) on S_1, S_2, and S_3, respectively.
S_1_(DSE), S_2_(DSE), S_3_(DSE)	The scenarios assumed a 5% improvement in reducing diesel consumption (DSE) on S_1, S_2, and S_3, respectively.
S_1_(PA), S_2_(PA), S_3_(PA)	The scenarios assumed a 5% improvement in recycling of paper wastes (PA) on S_1, S_2, and S_3, respectively.
S_1_(PL), S_2_(PL), S_3_(PL)	The scenarios assumed an increase of 5% improvement in the recycling of plastic wastes (PL) on S_1, S_2, and S_3, respectively.
S_1_(NH_3), S_2_(NH_3), S_3_(NH_3)	The scenarios assumed an increase of 5% in reducing ammonia emission (NH_3) on S_1, S_2, and S_3, respectively.
S: Scenario, RR: Resources Recovery, TR: Transportation, EL: Electricity, DSE: Diesel, PA: Paper, PL: Plastic	

Scenario one (S_1): describes the current practice for the MSW in Dar city of Tanzania. Scenario two (S_2): This scenario assumes recyclable materials (10%) are recycled, organic wastes (44.5%) are composted, and residue wastes (45.5 %) are landfilled. Scenario three (S_3): Under this scenario, recyclable materials (10%) are recycled as per current practice, organic wastes (44.5%) are treated in an anaerobic digestion process, and the residue wastes (45.5 %) are landfilled. In composting and anaerobic digestion processes, the treatment is assumed to be carried out in batch-wise operation as recommended in the literature (Igoni, Ayotamuno and Chibuogwu, 2008). Scenarios (S_1_RR, S_2_RR and S_3_RR) were as per scenarios S_1, S_2 and S_3, but with the inclusion of impacts of avoided environmental emission due to resource recoveries (production of electricity and mineral fertilizers). Scenarios (S_1_TR, S_2_TR and S_3_TR) assumed an increase of 5% in transportation (TR) of wastes in scenarios (S_1, S_2, and S_3). Scenarios (S_1_EL, S_2_EL and S_3_EL) assumed a 5% improvement in reducing electricity consumption (EL) in scenarios (S_1, S_2, and S_3). Scenarios (S_1_CH_4, S_2_CH_4 and S_3_CH_4) assumed a 5% improvement in reducing methane emission in scenarios (S_1, S_2, and S_3). Scenarios (S_1_DSE, S_2_DSE and S_3_DSE) assumed a 5% improvement in reducing diesel consumption in scenarios (S_1, S_2, and S_3). Scenarios (S_1_PA, S_2_PA, and S_3_PA) assumed a 5% improvement in the recycling of paper waste in scenarios (S_1, S_2, and S_3). Scenarios (S_1 _PL, S_2_PL, and S_3_PL) assumed a 5% improvement in the recycling of plastic wastes in scenarios (S_1, S_2, and S_3). Scenarios (S_1_NH_3, S_2_NH_3, and S_3_NH_3) assumed a 5% improvement in reducing ammonia emissions in scenarios (S_1, S_2, and S_3).

Life cycle inventory

Inventory data used in the study were obtained through various sources including; published literature, computational from MSW of the study area, and on-site investigations at the existing landfill at Pugu Kinyamwezi. Other information was collected from the Umberto LCA+ software library and ecoinvent 3v6 database (Accessed from the Michigan server of the USA). In Dar es Salaam City, the waste collected is disposed of at the Pugu Kinyamwezi landfill, located 30 km from the city centre. Therefore, the Umberto software computed the environmental impacts of the transportation based on the estimated distance per ton based on 1800 trucks, each carrying 5.0 tons of waste, at a round trip distance of 30 km daily. We selected and applied the transport truck" Transport, freight, lorry, 3.5-7.5, a metric ton (Rest of World - ROW)" from the ecoinventv3 database of the Umberto LCA software. In the analysis, we assumed the recycling, composting, and anaerobic digestion to occur at the existing Pugu landfill. The study considered the manual waste sorting by the waste pickers at the landfill. It was also assumed the consumers of the recycled materials bear the burdens of the recycling activity, and their emissions were excluded from the analysis. With regards to composting, we considered windrow composting with typical diesel requirements of 0.47 litres per ton (Sharma and Chandel, 2017). The indirect emissions due to diesel consumption were obtained from Umberto LCA+ software and the ecoivent v3.6 database. Due to the lack of data in a study area and since the nature of organic wastes is approximately similar in Tanzania, we adapted the amount of carbon and nitrogen from the MSW compositions of Arusha City (Omari *et al.*, 2014). The emissions due to methane and ammonia were computed as 1.1% of the fraction of degraded carbon and 19.5% of the total nitrogen present during the composting process (Amlinger, Peyr and Cuhls Carsten, 2008; Haaren, Themelis and Barlaz, 2010). The leachates generated in the composting process are assumed to be recycled throughout the process; therefore, their emissions in water were not considered in the analysis. With the anaerobic digestion process, the study applied the modified Buswell equation and typical elemental compositions of MSW of the study area to quantify emissions. The results showed that about 169,493 kg of methane would be obtained during the AD process (Belboom *et al.*, 2013; Richard *et al.*, 2021). It is estimated that the AD process has an electrical consumption of 4.4 kWh and an average electrical potential recovery of 205 kWh per metric ton of MSW (Kaza and Bhada-Tata, 2018). Tanzania's projected main energy source is hydropower due to the considerable investment of 2115 MW under-construction Rufiji hydroelectric power (Dye *et al.*, 2019). Therefore, the analysis considered the hydroelectric power in analyzing avoided environmental burdens due to electricity production. Literature indicates that processing one metric ton of organic waste in the AD process would generate about 100 kg of digestate (Khandelwal *et al.*, 2019). When the wastes with similar composition were applied, the ecoinvent database indicated about; N: 0.629%, P_2O_5: 0.331%, and K_2O per kg of fresh digestate could be generated. This information was crucial for estimating the quantity of nutrients (nitrogen and phosphorus) in MSW compositions during the AD and composting process. The ecoinvent v3.6 database in Umberto LCA software supplied data for the emissions of the recyclable materials, including; plastic, scrap metals, and glass wastes that are landfilled. Emissions due to organic matter degradation in a landfill were computed per the methodology described by Lee, Han and Wang, (2017). It is estimated that landfilling process has an electrical consumption of 0.42 kWh and an average electrical potential recovery of 65 kWh per metric ton of MSW (Boldrin *et al.*, 2009; Rajaeifar, Tabatabaei and Ghanavati, 2015). Table 2 depicts the inventory data for the three major scenarios: S_1, and S_3. The study generated the rest of the scenarios from these three scenarios.

Table 2: Inventory data under each scenario per daily MSW generation in Dar City

Parameters	**Unit**	**S_1**	**S_2**	**S_3**	**Ref.**
Background data					
Electricity consumption	kW h	3,402	-	17,622	(Igoni, Ayotamuno and Chibuogwu, 2008; Abduli *et al.*, 2011)
Diesel	L	24,300	14,167	12,285	(Hong, Li and Zhaojie, 2010; Rajaeifar, Tabatabaei and Ghanavati, 2015)
Emissions					
Ammonia (NH_3)	kg	20.02	7,599	2,860	This study
Methane (CH_4)	kg	169,493	4,966	35,973	This study
Nitrogen oxides (NOx)	g	44,469	44,469	760,950	(Oyoo, Leemans and Mol, 2014)
Total Nitrogen (TN)	kg	17,045	-	-	
Total Phosphorus (TN)	kg	26,914	-	-	
Particulates, < 10 um	g	4,489	4,489	1,172	(Rajaeifar, Tabatabaei and Ghanavati, 2015)
Sulphur dioxide (SO_2)	g	1,011	1,011	12,015	
Avoided products					
Electricity	kW h	260,325	-	821,025	(Kaza and Bhada-Tata, 2018)
Fertilizer (N)	kg	-	2,002	2,519	(Boldrin *et al.*, 2009), Ecoinvent database
Fertilizer (P)	kg	-	2,403	1,326	
Fertilizer (K)	kg	-	11,614	1,982	

Life Cycle Impact Assessment

The environmental impacts of the scenarios were assessed using the ReCiPe 2008 Midpoint (H) V1.13 which is one of the few updated methods in ecoinvent version 3.6. In addition, the Umberto LCA+ software was used to evaluate the impact categories. The emissions from MSW are likely to cause impacts on air, water sources and land. Therefore, the categories selected were climate changes, freshwater ecotoxicity, freshwater eutrophication, human toxicity, particulate matter formation, photochemical oxidant formation, terrestrial acidification and terrestrial ecotoxicity.

Principal component analysis for the selection of the most sustainable scenario

The environmental impacts of the scenarios obtained in LCA were the inputs to the PCA. We used the origin software version 9 to perform the PCA calculations. In origin software, the PCA computation is possible for the data with more observations than variables. The observations in this context are scenarios to be compared, and the variables are environmental impacts resulting from scenarios. The study used the origin software's descriptive function to standardize data before the PCA. The PCA computed the correlation matrix and eigenvalues named principal components

(PCs) that describe data variances based on the input variables. Accordingly, PC1, PC2, and PC3 explained the most, second, and third most variances, respectively. We used several criteria to select the number of PCS that explain the variance in the data. Firstly, a criterion of > 90% accumulative contribution by PCs to the variance of the correlation matrix. Secondly, a PC accounted for at least 5% of the data variation and eigenvalues were > 1. Lastly, according to the turning point of the eigenvalues change in the Eigen distribution scree plot. The PCA also computed scenario scores and loadings of each environment impact for each PC. The more sustainable scenario was the one with the lowest score value. The study also used the score values to determine the most sensitive parameters for improving different scenario processes. The scores range and percentage of the improvement before and after process improvement was conducted to assess the process that significantly impacted the environmental impact scenarios.

Sensitivity Analysis

The sensitivity analysis was performed to analyze which process would impact scenarios significantly. This was achieved through an increase of 5% in transportation and recycling of plastic and paper wastes, reducing electricity consumption, methane emission, diesel consumption, and ammonia emission on S_1, S_2, and S_3, respectively. Then variability in terms of range in combined scores of the principal components before and after improvements were determined.

RESULTS AND DISCUSSION

Results of life cycle analysis

Environmental impacts of scenarios

The environmental impacts of Scenarios: S_1, S_2 and S_3 are presented in Table 3.

Table 3: Environmental impacts of the scenarios

Category	**S_1**		**S_2**		**S_3**	
	Value	**Process**	**Value**	**Process**	**Value**	**Process**
Freshwater eutrophication (kg P eq)	26,952	Phosphorus (99%)	35	Transport (95%)	42	Transport (81%)
Human toxicity (kg1,4-DCB eq)	77,718	Transport (93%)	75,049	Transportation (97%)	79,295	Transport (93%)
Particulate matter formation (kg PM_{10})	927	Transport (57%)	3,193	Ammonia (76%)	1,836	Ammonia (50%)
		Diesel (42%)		Transport (17%)		Transport (29%)
Freshwater ecotoxicity (kg 1,4-DCB eq)	4,817	Transport (91%)	4,625	Transport (95%)	4,798	Transport (92%)
Terrestrial ecotoxicity (kg 1,4-DCB eq)	86	Transport (98%)	86	Transport (97%)	86	Transport (97%)
Photochemical oxidant formation (kg NMVOC eq)	4,390	Methane (68%)	2,205	Transport (63%)	3,172	Transport (44%)
		Transport (32%)		Diesel (33%)		NOx (24%)
Terrestrial acidification (kg SO_2 eq)	1,874	Transport (58%)	20,139	Ammonia (92%)	8,934	Ammonia (78%)
		Ammonia (49%)		Transport (5%)		Transport (12%)

Photochemical oxidant formation (kg CO_2 eq)	4.2 × 10^6	Methane (91%)	450,510	Transport (64%)	1.1 × 10^6	Methane (70%)
		Transport (7%)		Methane (24%)		Transportation (25%)

When comparing the three MSWM scenarios, S_1 showed high environmental impacts on categories of freshwater eutrophication, freshwater ecotoxicity, photochemical oxidant formation and climate change. Most of the methane emission in a landfill is not captured and was the significant contributor to photochemical oxidant formation and climate change in S_1. In S_3 (AD), the methane generated is high but used for electricity production, and in S_2 (Composting), the methane generation is very low. Similar observations were reported in other studies that methane is the major contributor to photochemical oxidant formation and climate change (Maalouf and El-Fadel, 2019). Similarly, the S_1 had high freshwater eutrophication due to phosphorus nutrient enrichment. Conversely, in S_2 (composting) and S_3 (AD), emissions due to water were not considered since the leachate was assumed to be recycled continuously, resulting in lower freshwater eutrophication. Ammonia emissions during the composting process were the major contributor to particulate matter formation and terrestrial acidification in S_2. Other studies elsewhere have also reported similar findings Haaren, Themelis and Barlaz, 2010). Transportation of wastes affected all the scenarios and was the dominant factor for human toxicity, freshwater ecotoxicity, and terrestrial ecotoxicity impact categories. Thus, promoting waste recovery technologies at the source of waste generation would significantly lead to minimizing environmental impacts. The environmental impacts of all other scenarios are given as supplementary data.

Results of Principal Component Analysis

Principal Characteristics Index of Variables

Table 4 provides the correlation coefficient matrix of the PCA of environmental categories for 27 scenarios.

Table 4: Correlation matrix of the principal component analysis of environmental categories for 27 scenarios

	Freshwater eutrophication	Human toxicity	Particulate matter formation	Freshwater ecotoxicity	Terrestrial ecotoxicity	Photochemical oxidant formation	Terrestrial acidification	Climate Change
Freshwater eutrophication	1.00	0.23	-0.80	0.31	0.44	0.11	-0.79	0.98
Human toxicity	0.23	1.00	-0.47	0.92	0.73	0.07	-0.48	0.32
Particulate matter formation	-0.80	-0.47	1.00	-0.34	-0.36	-0.04	1.00	-0.89
Freshwater ecotoxicity	0.31	0.92	-0.34	1.00	0.71	0.11	-0.34	0.34
Terrestrial ecotoxicity	0.44	0.73	-0.36	0.71	1.00	0.16	-0.37	0.44

Photochemical oxidant formation	0.11	0.07	-0.04	0.11	0.16	1.00	-0.02	0.09
Terrestrial acidification	-0.79	-0.48	1.00	-0.34	-0.37	-0.02	1.00	-0.89
Climate Change	0.98	0.32	-0.89	0.34	0.44	0.09	-0.89	1.00

According to the correlation coefficient matrix, the absolute value of the correlation coefficients which exceeds 0.4, indicates a correlation between variables. For instance, climate change is strongly positively correlated with freshwater eutrophication (0.98) while negatively correlated with particulate matter formation (-0.89) and terrestrial acidification (-0.88). This strong positive correlation could be attributed to emissions occurring during waste transportation, as presented in Table 3. Li *et al.* (2021) also indicated that both direct and indirect factors such as organic carbon and nutrients could affect freshwater eutrophication and climate change.

On the other hand, particulate matter formation is positively correlated with terrestrial acidification (correlation coefficients of 0.99). The high positive correlation of the latter could be attributed to ammonia emissions during the composting process. Human toxicity positively correlates with freshwater and terrestrial ecotoxicity (with correlation coefficients of 0.91 and 0.72, respectively). The high correlation is due to the waste transportation emissions (see Table 3).

Ranking of scenarios for sustainability assessment

Table 5 summarizes the PCA results of the correlation matrix of the variables. The eigenvalues and percentage variance contributions rate of the first three columns reached 91.18%. Each of the eigenvalues was greater than one and accounted for at least 10% of the percentage of variances. In addition, Figure 1 depicts a scree plot in which eigenvalues are easily identified by looking at the elbow of the line plot. Therefore, the three principal components were combined to obtain the combined score for each scenario (Table 6). The combined score was computed as a combined score = 0.5679*PC1 + 0.2187*PC2 + 0.1252*PC3.

Table 5: Eigenvalues of the correlation matrix

Principal Component	Eigenvalue	Percentage of variance	Cumulative
1	4.5435	56.79%	56.79%
2	1.7493	21.87%	78.66%
3	1.0020	12.52%	91.18%
4	0.4692	5.86%	97.05%
5	0.2340	2.93%	99.97%
6	0.0017	0.02%	100.00%
7	0.0003	0.00%	100.00%
8	0.0001	0.00%	100.00%

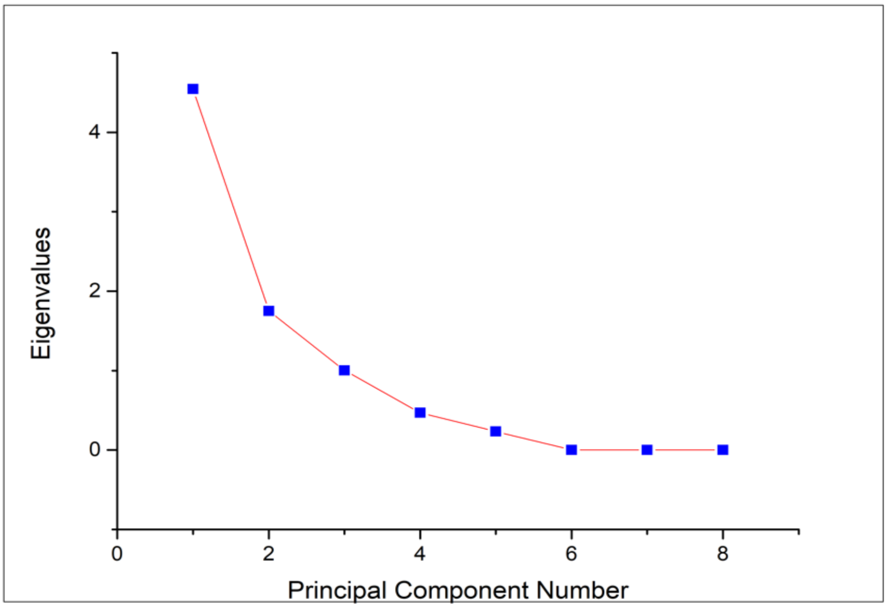

Figure 1: The scree plot for visualization of the principal component

Table 6: The principal component analysis of the MSW treatment scenarios

	Principal Component 1	**Principal Component 2**	**Principal Component 3**	**Combined score**
Scores labels				
S_1	1.1502	-0.5931	0.1086	0.5371
S_2	-0.8442	0.7672	-0.3650	-0.3573
S_3	0.0733	0.7738	-0.5005	0.1482
S_1 _RR	1.0969	-0.7212	0.1347	0.4821
S_2 _RR	-2.1243	-2.4214	0.2036	-1.7105
S_3 _RR	-1.2426	-2.5138	0.1260	-1.2397
S_1_TR	0.6951	-1.6593	0.2170	0.0590
S_2_TR	-1.4400	-0.5837	-0.3022	-0.9833
S_3_TR	-0.5124	-0.5563	-0.4344	-0.4670
S_1 _EL	1.2815	-0.3292	0.1542	0.6751
S_2 _EL	-0.8442	0.7672	-0.3650	-0.3573
S_3 _EL	0.0623	0.7436	-0.4882	0.1369
S_1 _CH$_4$	1.2603	-0.2989	0.1199	0.6653
S_2 _CH$_4$	-0.8518	0.7539	-0.3681	-0.3649
S_3 _CH$_4$	0.0724	0.7873	-0.5060	0.1500
S_1 _DSE	1.2556	-0.4021	0.1391	0.6425
S_2 _DSE	-0.8676	0.7069	-0.3747	-0.3850
S_3 _DSE	0.0627	0.7414	-0.5058	0.1344
S_1 _PA	1.2840	-0.3224	0.1520	0.6777
S_2 _PA	-0.8511	0.7532	-0.3672	-0.3646
S_3 _PA	0.0775	0.7823	-0.4992	0.1526
S_1 _PL	1.2840	-0.3224	0.1520	0.6777
S_2 _PL	-0.8511	0.7532	-0.3672	-0.3646
S_3 _PL	0.0775	0.7823	-0.4992	0.1526

S_1 _NH_3	1.2842	-0.3225	0.1519	0.6778
S_2 _NH_3	-0.6740	1.1602	4.7850	0.4701
S_3 _NH_3	0.0858	0.7741	-0.5017	0.1552

Accordingly, as seen in Table 6, the PCA results from the first principal component and combined score indicated that scenario (S_2 _RR) would be the most sustainable scenario with the combined score (-1.7105). This scenario combines recycling, composting and landfilling with the inclusion of avoided environmental burdens due to mineral fertiliser production (Nitrogen and Phosphorus). In most PCA analyses, the zero-value scenarios or 'do nothing scenario' indicate the most sustainable value (Helness *et al.*, 2019). However, the negative value in this analysis indicates an advantage due to avoiding environmental emissions. Thus, the scenario with high negativity represents the more sustainable option. In the loading plot (Figure 2 and Table 7), we can see that climate change and freshwater eutrophication have similar heavy loadings for principal component 1. The results demonstrate that climate change and freshwater eutrophication which both contribute to the rate of 56.79%, were the critical factors in environmental burdens in all scenarios. In scenario two, the most sustainable option, climate change and freshwater eutrophication were the lowest compared to other scenarios.

CONCLUSION AND RECOMMENDATION

This study analyzed the environmental impacts and sustainability of Dar es Salaam City municipal solid waste management scenarios using a novel two-stage lifecycle-based principal component analysis. The life cycle assessment results indicated that the S_1 (recycling and landfill) has the most adverse environmental categories except for human toxicity, terrestrial acidification and particulate matter formation. The S_2 (recycling composting and landfill) has the highest environmental categories of particulate matter formation and terrestrial acidification. On the other hand, the S_3 (recycling, anaerobic digestion and landfill) leads to the highest environmental categories of human toxicity. In the second phase, the study utilized the PCA methodology and the life cycle analysis results to perform the sustainability assessment on scenarios. Based on the PCA results, S_2, the combination of the landfill, recycling, and composting, was found to be a more sustainable option. The sensitivity analysis revealed that waste transportation is a more critical and sensitive process. Thus, reducing the transportation distance through promoting waste recoveries at the source would significantly reduce the environmental impacts of the scenarios. This study demonstrated that the proposed novel two-stage lifecycle-based principal component analysis could be applied to support the decision-making process on the most sustainable MSW option.

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Declarations

The authors declare no conflict of interest.

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