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A MCDM-LCA and Cluster Analysis-based Scenario Analysis for Sustainable Integrated Solid Waste Management System in Ibadan, South-West Nigeria

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Abstract **Original Research Article**

The annual waste generation is expected to increase to 3.40 billion tons in 2050. Although there are generally accepted global best practices in Waste Management (WM), there is no all-in-one WM approach, metrics, or strategy that fits all societies in the globe due to the peculiarities of every environment. There is a need to design and adapt sustainable waste management standards, metrics, and strategies in every location, depending on the prevailing social, economic, and human factors in such localities, considering different feasible scenarios. This work proposes an MCDM-LCA-based scenario analysis framework that takes care of the uncertainty inherent in solid waste management systems and designs. It integrates an Analytic Hierarchy Process (AHP) and Life Cycle Assessment (LCA) using cluster analysis (CA). The framework is applied using the information from the decision makers who are waste managers, experts, and stakeholders. Different arrangements of waste treatment methods and scenarios were formulated and analyzed using the data obtained from the field. The best scenario (formed from the aggregation of scenarios 8 and 9) favors 42% of the waste being sent to an anaerobic digestion facility, 20% to compost, 18% to refuse-derived fuel, 15% to recycling, 5% to an incinerator, and the remaining 5% to the landfill.The proposed design presents the best set of scenarios for the effective and sustainable integrated solid waste management system (SISWMS) with three major sub-which are environment, social, and economic, considering the peculiarity of the system with available resources and constraints. Even in difficult terrains. It incorporates easy, yet flexible methods of solving complex solid waste management problems, which are adaptable to various localities based on their structures, norms, settings, and peculiarities. This work presents useful metrics that serve as the basis for taking management decisions, setting targets, and making action plans to weigh different waste treatment options that fit a particular location. It will minimize uncertainty and enhance sustainability in WM designs and operations.

Keywords: Sustainability, Scenario analysis, Sustainable Integrated Solid Waste Management, Ibadan-North LGA, Southwest Nigeria.

1.0 INTRODUCTION

Municipal solid waste (MSW) is the waste generated by people daily as they live and work, including the waste from the service sector (like hospitals, shops, hotels, and restaurants). MSW does not include industrial waste, agricultural waste, and sewage sludge (Al-Rumaihi et. al. 2020). Waste generation in sub-Saharan Africa is approximately 62 million tons per year, while the per capita waste generation ranges from 0.09 to 3.0 kg per person per day, with an average of 0.65 kg/capita/day (Alzamora & Barros, 2020; Sharma & Jain, 2020). Dangerous and harmful gases are released into the atmosphere, which alters the climate through heating and pollution (Ameli et.al., 2023). Multitudes migrate to towns and urban areas in search of greener pastures and better condition of living leading to an increase in the volume of waste being generated, thus creating public health problems. SWM involves activities associated with generation, storage, collection, transfer and transport, treatment, and disposal of solid wastes (Behzad et.al.,2020; Bisinella et.al., 2021; Brancoli, Bolton & Eriksson, 2020). The challenges remain in the implementation of an integrated as well as a sustainable SWM structure, as comprising all waste treatment and management aspects being handled by relevant and competent stakeholders (Mir, Cheema & Singh 2021; Oluwanimifise & Anyaeche, 2021). Since the SWM problem is a global challenge occasioned by an exponential increase in population, rapid urbanization, industrialization, inefficient utilization of natural resources, lack of citizen awareness regarding the environmentally adequate disposal of waste, consumption, socioeconomic status (lifestyle), and others. (de-Sadeleer, Brattebø & Callewaert, 2020; Ferronato, et. al., 2020; Tomić, & Schneider, 2020; D'Inverno, Carosi & Romano,2024).

The global distribution of pollutants by waste collections all around the world is at the most extreme level, and all these environmental catastrophes are derived from consumption (Slorach et.al., 2020). In the simplest definition, the environmental impacts of heavily consumerist lifestyles are sharply rising, and Africa is no exception to this crisis. Sub-Saharan African countries are presently in the early stages of their urbanization process. Africa was the least urbanized region in the world in 2015 (only 40% of sub-Saharan Africa's population lived in cities), and now it is the second fastest urbanizing region in the world-behind Asia (Colvert et al., 2020). Compared to those in developed nations, residents in developing countries, especially the urban poor, are more severely affected by unsustainable managed waste. In low-income countries, over 90% of waste is often disposed of in unregulated dumps or openly burned. These practices create serious health, safety, and environmental consequences (Fořt & Černý, 2020; Istrate et. al., 2020).

A scenario is a coherent sequence of plausible events and decisions that creates a vivid, compelling structure of what the future might look like (Hoa et.al., 2024). This helps to stretch the thinking of the decision makers, enabling them to have a broader range of possibilities, thereby identifying better and more creative strategies. It can also help in forecasting the consequences of strategic choices. Scenarios alone do not predict the future but provide the basis to "pressure test" strategies and their robustness (Menegaldo et. al.,2023). Also, scenarios suggest the leading indicators and variables to monitor (Campitelli & Schebek, 2020). Scenario analysis (SA) is a part of strategic planning that helps to create a number of plausible future realities. It is a process of quantitative evaluation of possibilities and probabilities of the scenarios. SA helps to create multiple different environment realities in which the future is going to occur, thereby rescuing the future by creating plans at every point to guide decision-making. (Schnaars,1987). It starts with the identification of the key uncertainty in the sector to be analyzed, and simultaneously provides a solid base for planning and forecasting to enhance a versatile and adaptable SISWMS (Shammi, 2021). The process or steps towards an effective, viable, and efficient scenario analysis are presented in the figure below:

Fig.1: Scenario Analysis. Source: Oluwanimifise and Anyaeche,2021

There are many ways of evaluating SWM practices and operations. They could be broadly grouped into three methods according to different theories: cost-benefit analysis (CBA), Multicriteria decision analysis or methods (MCDA or MCDM), and Life Cycle Analysis or assessment (LCA) (Schmidt, et.al., 2020; Zhang, Qin & Tseng, 2021). LCA is the assessment of the environmental and resource impacts caused by the activities needed for fulfilling certain functions, considering the entire life cycle of a product and/or services from cradle(beginning) to the grave (end) (Zhao et. al., 2021; Ioan-Robert et.al., 2022). It consists of four stages: goal definition, life cycle inventory analysis, life cycle impact analysis, and valuation. It analyses all relevant environmental impacts based on mass flows aggregated over the entire life cycle. The typical results of an LCA are an environmental impact profile. Life cycle assessment (with inventories) addresses environmental aspects and the potential environmental impacts (for instance, the use of resources and the environmental consequences of hazardous release) throughout a product's life cycle from raw material acquisition through production, use, end–of–life treatment, recycling, and final disposal (Sauve & Van-Acker 2020). The goal definition stage (which is a routine procedure) is the stage where options are compared, the intended use of results is defined and stated, and the functional units, as well as the system boundary, are stated. The life cycle inventory (LCI) analysis accounts for all materials input and output across the whole life cycle. The life cycle inventory analysis, also known as classification, involves the conversion of the life cycle inventory of materials and energy into their environmental effects (Sharma & Chandel, 2021). This stage is still evolving as it requires more contribution from the researchers on the classification of all environmental problems into effects, units of measurement, and the conversion of LCI into units within each effect. The evaluation stage handles the decision-making between the options of different impact categories, as well as that of the inventory category, using a single environmental score (Wang, et. al., 2020). This requires some form of weighting of the importance of different environmental problems. The aggregation of all impacts to a single score makes the assessment easier, but the assumptions of the measure are obscure, making the general acceptance uncertain. (Iqbal, Liu,& Chen, 2020). This work combines LCA with the multi-criteria decision-making (MCDM) method-AHP) to perform the weighting for the scenarios.

MCDM refers to deciding the presence of multiple, usually conflicting criteria. There exist two types of MCDM: those with a finite number of alternative solutions and the other with an infinite number of solutions. Its problems are complex, complicated, and usually of a large scale, represented in the form of alternatives having a different number of attributes in each alternative. (Palafox-Alcantar, Hunt Y Rogers, 2020). The problem is designated in the form of a decision matrix. Suppose there are m alternatives to be assessed based on n attributes. A decision matrix is an m × n matrix with each element Y_{ij} being the jth attribute value of the i-th alternative. The attribute can be quantitative or qualitative, deterministic or probabilistic(stochastic). MCDM employs the use of compensatory and non-compensatory methods to solve problems (Torkayesh et. al., 2022). The compensatory methods permit trade-offs between the attributes. That is, a decline in one attribute is acceptable if it is compensated for by some enhancement in one or more other attributes. These could be scoring, compromising, concordance methods, and the evidential reasoning approach. The scoring methods select or evaluate an alternative according to its utility as expressed by the decision maker's preference. The non-compensatory methods (in which trade-off is not permitted) are: dominance, maximin, maximax, conjunctive constraint, and disjunctive constraint methods. Examples of scoring methods are the additive weighting method and AHP, to mention a few. Calculates the scores for each alternative by pairwise comparison. AHP is very popular and widely used in waste management problems (Saaty,1998; Saaty and Vargas, 2001).

Cluster Analysis (CA) is the art of dividing data into groups (clusters) that are meaningful, useful, or both for understanding or utility. Oftentimes, CA is the starting point for other purposes such as data summarization, data mining, and pattern recognition, to mention a few(Du et al., 2022). A cluster is a set of objects in which the objects are closer or similar to every other object in the cluster than objects not in the cluster.CA is used wide variety of fields: psychology, biology, statistics, machine learning, and information retrieval. Various form of clustering is distinguished as hierarchical (nested) versus partitioned (unnested), exclusive versus overlapping, versus fuzzy, and complete versus partial. Clustering aims to find a useful group of objects where usefulness is defined by the goals of the analysis (Hendrik et al., 2022). The different types of clusters could be: well separated, prototype-based, graph-based, contiguity-based, density-based, and shared-property (conceptual clusters). The internal measure of cluster validity for a partitional clustering scheme is based on the notion of cohesion and separation. In this work, measures for prototype- and graph–based clustering techniques are employed. The relationship between the prototype and graph-based clustering for a set of K-clusters is given as a validity function, which could be cohesion, separation of the clusters, or some combination of these quantities. The overall validity function for a set of k clusters is the weighted sum of the individual clusters.

The researchers have employed various approaches to capture uncertainties and minimize their effects. Tools like fuzzy logic, grey fuzzy, Analytic Hierarchy Process (AHP), Fuzzy Analytic Hierarchy Process (FAHP), Life Cycle Assessment (LCA) method, and other Multicriteria Decision Making Analysis and Methods (MCDA and MCDM). The principles and process of AHP, FAHP, and LCA are explained in (Ong et. al., 2020; Tonini et.al., 2020; Towa, Zeller & Achten, 2020; Paes et.al., 2020; Shahsavar et. al.,2022; Mulya et. al.,2022; Zadeh, 1978)

In the field of waste management, researchers have demonstrated the use of methods like scenario development (SD), scenario analysis (SA), strategic environmental assessment (SEA), material flow analysis (MFA), environmental impact assessment (EIA), risk analysis (RA), cost benefit analysis (CBA) and operation management (OM) which could be linear programming(LP), non-linear programming (NLP), mixed integer programming (MIP), dynamic programming (DP). This could be achieved through an integrated modelling system (IMS), expert system (ES), decision support system (DSS), management information system (MIS), and systems thinking or dynamics, to mention a few (Winston,1994; Movahed, et.al., 2020; Ottoni, Dias & Xavier, 2020; Sobia-Riaz *et.al.*, 2022).

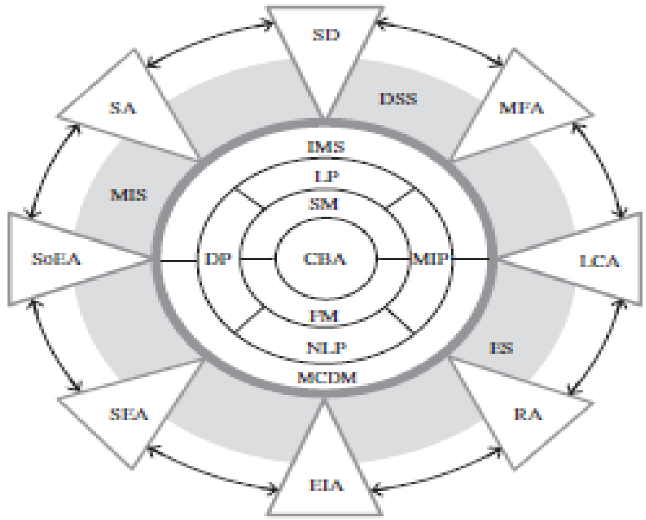


Fig.2: System engineering methods and tools for waste management

Source: Ni-bin Chang and Pires,2015

This work aims to bridge the gaps in performance measurement of WM practices and operations by proposing a new benchmark framework for SISWM. The framework is capable of choosing the best scenarios given certain waste treatment options and the peculiarity of a particular location. Also, the framework is sufficiently generic and flexible to allow incorporating other methods into the assessment, such as uncertainty analysis, economic analysis, and optimization. Section 2 describes the framework. Section 3 describes the mathematical formulation and aggregation. Section 4 presents the illustration and application of the framework. Section 5 draws the main conclusion and the future work.

2.0 MATERIALS AND METHODS

2.1 The goal and scope

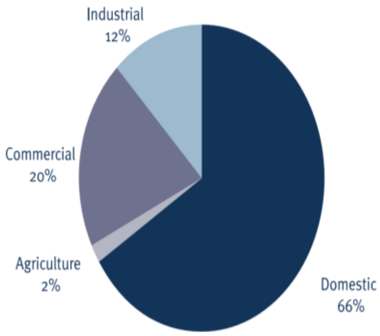
This work will formulate scenarios and propose a generic model that can pick the optimal or best scenarios among many options or alternatives. The scenario alternatives are formed by integrating five waste treatment techniques: Incineration, anaerobic digestion, composting, refuse-derived fuel, and recycling. Two transfer stations are designed for every waste-generating area to collect the mixed waste and the sorted waste. Curbside collection method is practiced, and the rest of the waste with the residue of the waste treatment processes, is finally dumped in both the sanitary and unsanitary dumpsites. There are many limitations in using the LCA method. The national database and standards for computation are not available in many developing countries. The previous works (on these developing countries) draw heavily from the literature and foreign software that are originally developed for the country in which they are made. Examples are the Dutch Simapro and the Ecoinvent. Howbeit, this study only requires the first stage of LCA: goal definition and scope.

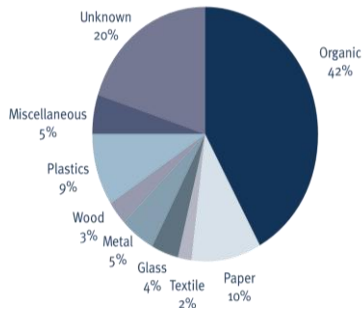
2.2 Composition, Characterization, and Disposal of Solid Waste in Ibadan and Its Environs

Due to population explosion, lavish lifestyles, and changing dietary habits, not only does the quantity of waste generation increase, but the quality as well as composition of the waste also change. Hence, with improvement in the standard of living of the people, the organic components of the waste decrease while the paper and plastic components increase.

Salawu (2018) submitted that the MSW in Ibadan emanates from four major sources as shown in Fig.1.1(a) above 66% is from the domestic activities,20% from the commercial activities,12% is from industrial activities, while 2% is from agricultural activities. Characterization of waste is necessary to know the changing trends in the composition of waste. Based on composition, characterization of waste, an appropriate selection of waste processing technologies could be made. The general composition of solid waste being generated from the cities of Ibadan is 42% Organic (Food and Garden) waste,4%glass and Ceramics,5% Metal, 9% Plastic/ Rubber, 2%Textile, 10 % Paper,5% miscellaneous, with 20 % unknown as shown in Fig.1.1(b) above.

It is evidently clear that waste disposal in Ibadan is still awful, as shown in.Fig.1.1(c). Only 15% of waste was collected, with 35% being burnt,28% being dumped at unapproved dumpsites, 16% on public approved dump sites,4% buried, and the rest 2% treated anyhow.





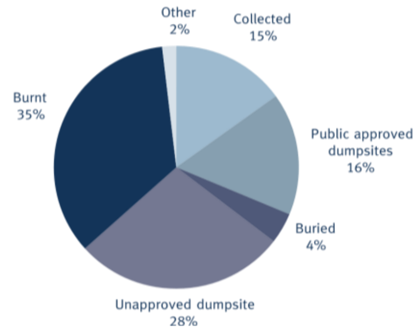


Fig. 3a: Sources of waste Fig3b. Waste composition Fig3c. Waste Disposal Methods

Source: World Bank PPIA,2017

2.3 The model's criteria and sub-criteria

Previous works have submitted that resources available and economic factors, policy, operational constraints, environmental impacts, technology, and social considerations like people's awareness and participation are the major drivers that influence solid waste management systems and design [22]. The Sustainable Development Goals (SDGs) centre on the tripod leg of environmental, economic, and social, which are the pillars of sustainable development. The SISWM is built on this tripod to ensure a viable, equitable, and bearable WM system that is sustainable. This is presented in the figure below:

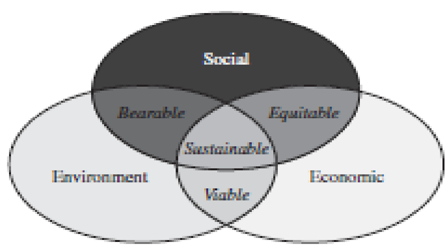


Fig.4: The major criteria of SISWMS

The choice of the best scenario or alternative is made by considering the interrelationship among the basic criteria, the ratings, and the weight of each criterial. The management of waste is a stochastic process with inherent uncertainties in every facet of its planning, operation, and administration. Based on the literature and the peculiarity of the locality of the area of study, the sub-criteria considered for the environment are: global warming (GWP), ozone layer depletion (OZL), human health and eco-toxicity (HHE). The three sub-criteria for the social are: people participation (PPT), people awareness and enlightenment (PAE), as well as the proximity and land use alternative (PLA) for the facilities. The sub-criteria considered from the economic perspectives are: design cost (DCST), operating cost (OPCST), set-up cost (SUCST), and contribution to the gross domestic product (CGDP).

2.4 The waste flow network

The SISWM presented in the figure below comprises nine points or nodes starting from the point of waste generation to the point of waste disposal. The design includes waste generation nodes, five waste treatment and processing facilities, two nodes for transfer stations, and a sanitary landfill.

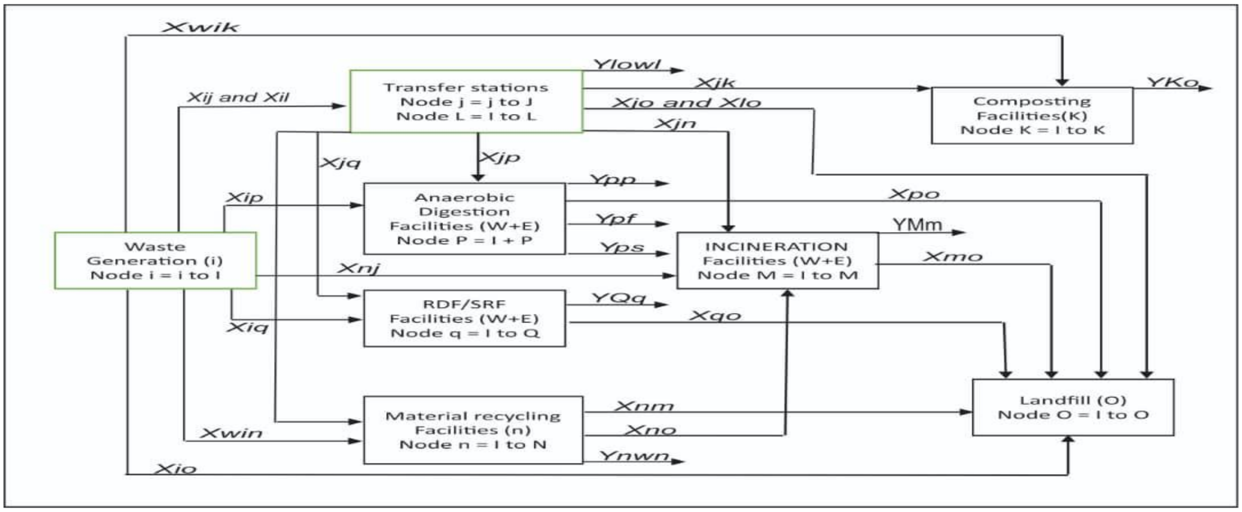


Fig.5: The waste flow network for SISWM

3.0 METHODOLOGY

3.1 Framework Description

Waste from three sources: households, commercial activities, and street cleaning is considered. The waste is collected using the curbside method at the transfer stations, where the mixed waste is separated. Anaerobic digestion plants, composting sites, incinerators, material recovery facilities, and other associated waste treatment processes. The intermediate waste stream produces recyclable material, energy, compost, and other secondary materials. In order to lessen the requirement of primary production, the intermediate waste stream is further processed, and the end goods are released into the market. Waste is brought from the nearest waste generation point (about 500m) to the transfer station. No waste is allowed to go from the point of generation to the landfill directly. The system is run by the local government authority using officers and professionals in the wards, while the state government sets the policy and enhances the enforcement. The study starts by searching for the required performance indicators (PIs) for the evaluation of WMS, identified from the literature review, and then used to develop a distinct and structured questionnaire that targeted: management officers from the government or regulatory institutions, private waste managers and contractors, health officers, landfill officers, and the people in the community. The questionnaires were used to sample the opinions of the degree of importance of the PIs on a 5-point Likert scale (1= not important and 5= very important). The relative importance index (RII) is given as:

$$RII = \sum_{i=1}^{5} \frac{W_i \, xX_i}{AXn} \dots \dots \quad (1)$$

Where W_i = the weight given to I_{th} response: I=1…5; X_i = frequency of the I_{th} response; highest weight (5 in this study), n = number of respondents.

3.2 Formulation and development of waste management scenarios

Due to the constraints in operations, resources, and technology, different waste management strategies (denoted as scenarios) were formulated and explored theoretically with data from the waste management handlers and stakeholders. Ten different alternatives or arrangements stand for scenarios. These are obtained from the various combinations of six different waste treatment options, which are: Landfilling option, Incineration option, Composting option, Recycling option, Anaerobic Digestion (AD) option, and Refuse Derived Fuel (RDF) option. The common treatment methods are used to create the scenarios. Ten different scenarios or arrangements were created with different percentages (or amounts) of solid waste for each waste treatment option based on the decision of the experts and the stakeholders, subject to waste composition, peculiarity of the locality, and prevailing circumstances at hand. The scenarios are stated below;

Scenario 1: Landfill (100%)

Scenario 2: Landfill (20%) + Incineration (80%)

Scenario 3: Landfill (20%) + compost (80 %)

Scenario 4: Landfill (20%) + Anaerobic Digestion (80%)

Scenario 5: Landfill (20%) + Refuse Derived Fuel (80%)

Scenario 6: Landfill (20%) + Recycling (80%)

Scenario 7: Landfill (10%) + compost (30%) + AD (30%) + RDF (30 %)

Scenario 8: Landfill (10%) + Incineration (30%) + compost (30%) + AD (30%)

Scenario 9: Landfill (10%) + compost (20 %) + AD (%) + RDF (20 %) + Recycling (30 %)

Scenario 10: Landfill (20%) +Incineration (20%) +Compost (20 %) +AD (20 %) +Recycling (20 %).

The global weight (GW_{ij}) = $SISWM_i$ X $LW_{ij,}$ where SISWM is the weight for the criteria and LW_{ij} is the local weight for all KPIs. I= indicator,I=1,2,3…n, J = Scenario,J=1…10

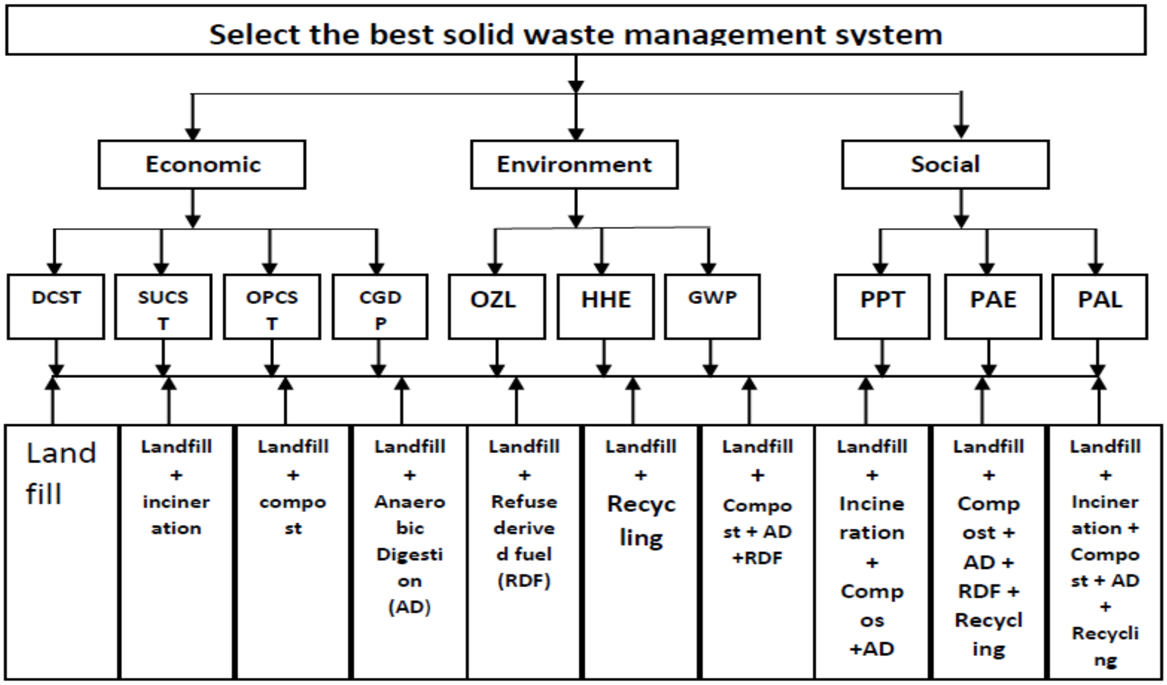


Fig.6: The SISWM goal, criteria, sub-criteria, and scenarios

3.3 The design of the study using the Analytical Hierarchy Process (AHP)

The choice of AHP in this work is based on its popularity and effectiveness in handling the WM performance measurement. Having stated the major goal, criteria, sub-criteria, and the scenarios (alternatives), the respective levels are run through the AHP comparison matrix to obtain the weights at the local and global levels for each of the criteria, sub-criteria, and scenarios as scored by the decision makers(DM) based on the questionnaire results. Pairwise comparison of each element in the hierarchy is done in order to rank all the criteria in every hierarchy. Using this comparison spoken assessment is translated into a number between 1 and 9. Whereas a score of 9 denotes that one criterion is far more important than the other, a score of 1 shows that two criteria are equally important. Mathematically, each criterion x1 for a collection of criteria [$x_{1,}$ x_2 …x_n] is assigned a weight w_1 based on an nxn comparison matrix A. The system of equations must be solved to determine the primary eigenvector w.

$$(A - \lambda I)W = 0 \qquad (1)$$

Where: I represents the unit matrix, W is the major eigenvector (or vector of priority factors),λ(lambda) is the principal eigenvalue of A. n is the number of criteria. The consistency index is calculated using the formula:

$$CI = \left[\frac{\lambda_{max} - n}{n - 1}\right] \qquad (3)$$

For more information about AHP models, concepts, and applications, see Saaty [27,28], Winston[42]. The DM in this study are experts and the stakeholders involved in waste management from both public and private sectors. The matrix is scored using the Saaty measurement scale. The matrix value of each sub-criterion having criteria A, B, and C for point i is given as ($A_{i,}$ B_i, C_i).The local weight LW_i at every point i for n number of data points X of every criterion and sub-criterion is calculated using:

$$LW_i = \sum \left[\frac{x_i}{\sum_n^i x}\right] \dots\dots\dots\dots (4)$$

The table for the main objective or goal having three sub criteria, with n criteria and n defined scenarios, is presented in tables 1,2, and 3, respectively, below:

Table 1: the pairwise comparison matrix table for the main goal with n sub-criteria

Main goal	Sub criteria 1	Sub criteria 2	…	Sub criteria n	Weight
Sub criteria 1	1	X	…	X	W1
Sub criterion 2	1/X	1	…	1/X	W2
….	…	…	…	…	…
Sub criteria n	1/X	1/X	…	1	Wn

Table 2: the pairwise comparison matrix table of a sub-criterion with n criteria

Sub criteria	Criteria 1	Criteria 2	…	Criteria n	Weight
Criteria 1	1	X	…	X	A1
Criteria 2	1/X	1	…	1/X	B1
…	…	…	…	…	…
Criteria n	1/X	1/X	…	1	N1

Table 3: the pairwise comparison matrix table of n scenarios of each sub-criterion

Sub criteria	Senario 1	Senario 2	…	Weight
Senario 1	1	X	…	A2
Senario 2	1/X	1	…	B2
…	…	…	….	…
Senario n	1/X	1/X	…	N2

The weights of all criteria, sub-criteria, and scenarios are calculated using equation 1. The Global weights or total weight of each criterion is obtained by multiplying the weight of each criterion by the weight of the sub-criteria under the main criteria. That is W1*A1,W2*B2 to Wn*N1.The total or final scores(AHP) of every scenario are obtained by finding the average of each scenario with respect to the sub-criteria weight. The AHP score is calculated using:

$$AHP_w = \sum_{i}^{1} W_{subcriteria\ i} \times W_{Subcriteria\ weight\ across\ the\ scenarios\ i \ldots n} \cdots\cdots. (5)$$

Afterwards, the scores are ranked respectively with the related score

3.4 Scenarios standardized AHP scores

AHP scores are normalized and prepared for weighting using:

$$SS_{AHP} = \frac{SS_i - M_{ssi}}{M_{ssi}} \ldots\ldots\ldots (6)$$

Where “SS_{AHP}“is the AHP score that has been standardized, SS_i is the AHP score for every scenario “i “, and M_{ssi} is the average of all AHP scores for every scenario.

3.5 The Life Cycle Analysis (LCA) of the scenarios under the five waste management Technologies.

This work encountered limitations, like the non-availability of data needed, among others, in the attempt to access the environmental impacts of the waste management technologies involved. Howbeit, only one of the four components of LCA (goal definition and scope) is required for this study. Data from the SimaPro 7.3 software for a related previous study using the same functional unit of 1 ton of solid waste are used as impact points in this work for the environmental criteria under the defined scenarios, as presented below:

Table 4. The environmental impacts of the environmental criteria

	Sce 1	Sce 2	Sce 3	Sce 4	Sce 5	Sce 6	Sce 7	Sce 8	Sce 9	Sce 10
GWT	0.011	0.224	0.00016	-0.004	0.0168	-0.0074	0.002	-0.005	0.004	-0.00
OLD	-0.0003	-0.0192	0.0464	-0.0008	-0.0004	-0.0008	0.058	-0.001	-0.00001	-0.02
HHE	0.013	0.8616	0.0144	-0.00068	0.0256	-0.0064	0.018	-0.0085	0.002	-0.07

The impact points for each scenario (L_i) are calculated using the template in Table 5 below according to the equation.

$$L_i = \sum_{1}^{10} S_{ij} W_i \dots\dots\dots (7)$$

Where L_i is the impact point, "S" is the corresponding score (1-10) for the "i" scenario associated with "j" criteria, and "W_j" is the weight of the "j" criteria

Table 5. Scoring template for the SISWM framework and design

Range of AHP weights	0 - 0.099	0.099–0.199	0.199–0.299	0.299–0.399	0.399–0.499	0.499–0.599	0.599–0.699	0.699 - 0.799	0.799–0.899	0.899–0.999
Score	1	2	3	4	5	6	7	8	9	10
Definition	Very bad	So bad	bad	Slightly bad	Not so bad	Averagely good	Slightly good	Good	So good	Very good

3.6 LCA standardized points for every scenario

The LCA points for the criteria under the environment sub-criteria are standardized using equation 5 below:

$$SS_i = -\left[\frac{SP_i - M_{Sp}}{M_{Sp}}\right] \dots\dots (8)$$

Where "SS_i" is the scenario standardized LCA points," Sp" is the scenario's LCA point, and $M_{sp.}$ is the average LCA points for every scenario "i". This is necessary to normalize and prepare the data.

3.7 Cluster Analysis Method of combining and plotting LCA and AHP

The standardized points of the LCA and the final AHP weights are mapped into clusters. Minimizing the space between the two clusters to a negligible distance culminates in each element from the two clusters forming the coordinates with the matched points in the cluster analysis. Then the LCA point makes the vertical coordinate, while the AHP makes the horizontal coordinate. The AHP and LCA scores, respectively, make up the coordinates of the points in the Cluster Analysis. The optimum points are those with the highest positive vertical and horizontal points.

The minimized squared Euclidean distance between each corresponding point in each cluster is given as:

$$DISTANCE_{xy} = \sum_{i}^{p} (x_j - y_j)^2 \dots\dots\dots \quad (9)$$

Points "*xj*" is the coordinate of the AHP cluster, while "*yj*" is the coordinate of the LCA cluster forming each point in the Cartesian coordinate. Each point represents each scenario. The uppermost point (scenario) to the right-hand (positive vertical and horizontal axis) is the optimum, while the lowest point on the left-hand side of the origin (negative vertical and horizontal axis) is the worst.

4. RESULTS AND DISCUSSION

4.1 The experts and stakeholders' judgement.

According to the judgment of the experts and the stakeholders**,** ascribing equal weight to the three main criteria and using it to multiply the local weights to obtain the global weights, the results of all the global weights are presented in the table below:

Table 6: The local and global weights for all the sub-criteria

MAIN CRITERIA	SUB CRITERIA	MAIN CRIT. WEIGHT	LOCAL WEIGHT IN (AHP)	GLOBAL WEIGHT (AHP)	Consistency Index
ENVIRONMENT	GWP	0.3	0.5310	0.1593	0.043
	OLD	0.3	0.3319	0.0996	0.063
	HHT	0.3	0.1372	0.0411	0.055
ECONOMIC	Design CST	0.3	0.1365	0.0409	0.067
	Set-up CST	0.3	0.2165	0.0649	0.091
	Oper. CST	0.3	0.6470	0.1941	0.034
	CGDP	0.3	0.4059	0.1218	0.075
SOCIAL	PLA	0.3	0.1938	0.0581	0.041
	PAE	0.3	0.4961	0.1488	0.049
	PPT	0.3	0.3101	0.0930	0.036

The experts and the stakeholders presented their decision on each of the sub-criteria in each of the scenarios through the comparison of the scenarios with respect to each of the sub-criteria. The average value across the scenarios is used in the study to reduce bias. The weight is presented below:

$$\text{The Sub criteria across the scenarios} = \begin{bmatrix} \text{Global warming pote.} & 0.026421 & CI = 0.00427 \\ \text{Ozone Layer Depletion} & 0.030850 & CI = 0.00762 \\ \text{Human Health\&Eco.} & 0.041055 & CI = 0.00550 \\ \text{Design cost} & 0.049025 & CI = 0.00717 \\ \text{Set} - \text{up cost} & 0.063764 & CI = 0.01087 \\ \text{Operating cost} & 0.081594 & CI = 0.00404 \\ \text{Contribution to GDP} & 0.133786 & CI = 0.00933 \\ \text{Proximity\&Land Alt.} & 0.144355 & CI = 0.00485 \\ \text{PeopleAwareness\&E.} & 0.219134 & CI = 0.00574 \\ \text{People participation} & 0.211876 & CI = 0.00476 \end{bmatrix}$$

The AHP weights are obtained from the judgment of the experts and the stakeholders applying Eq.(5) and Eq. (6). The picture of the waste management system from the environmental perspective, considering global warming, ozone layer depletion, human health, and ecotoxicity for all the scenarios, is presented in Figure 8.1a-c, respectively. The trend in the life cycle assessment of all the scenarios and the analytic hierarchy process ratings of all the scenarios are presented in Figure 8.1d below.

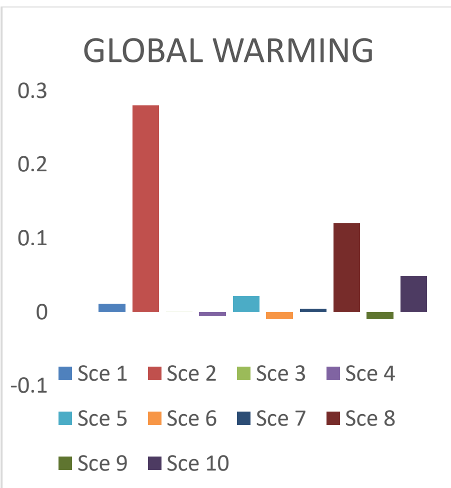


Fig.7.1a: Contribution to global warming by the scenarios

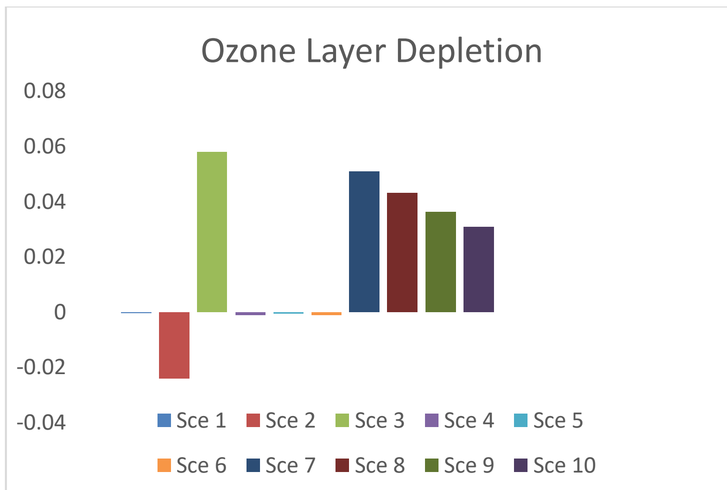


Fig.7.1b: Contribution to the ozone layer by the scenarios

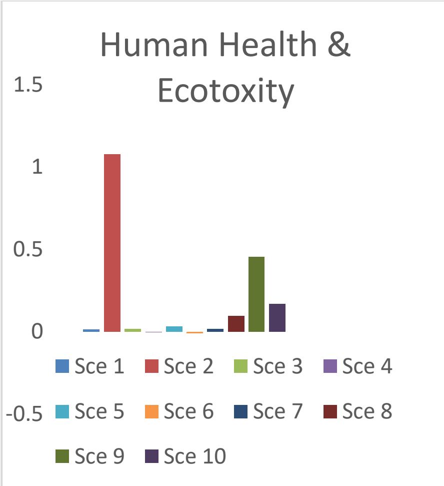


Fig.7.1c: scenarios' contribution to eco-toxicity and effect on human health

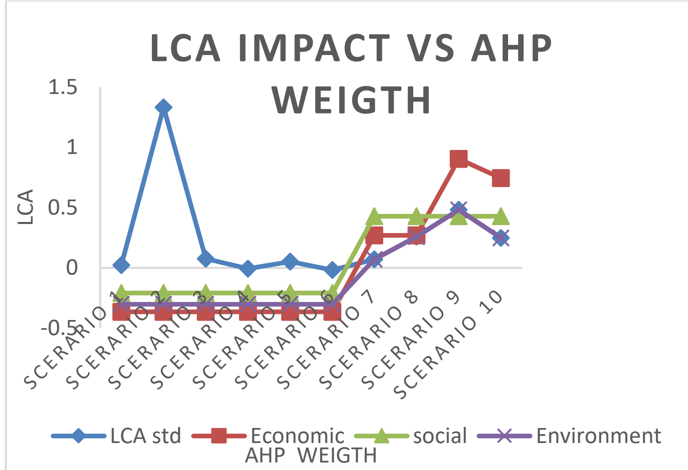


Fig.7.1d: Life cycle assessment versus the AHP ratings of the scenarios

Considering the global warming tendency shown in Figure 7.1a, scenarios 2, 8, and 10, respectively, pose the highest threat, which is not desirable. Scenarios 6, 9, and 3 have the optimum and are feasible and fit for the locality. Considering the ozone layer depletion shown in Figure 7.1b, scenarios 3,7,8,9and 10 respectively have the highest tendency to cause havoc, while scenarios 2.4.6,5 and 1 respectively are desirable and fit for the locality.

From the perspectives of human health and eco-toxicity, as shown in Figure 7.1c, scenarios 2,9,10, and 8, respectively, constitute the highest threat to human health and eco-toxicity. Scenarios 6, 4, 1, 3, and 5, respectively, are the best as regards being friendly with human health and the ecosystem. Figure 7.1d gives the trend across the scenarios from an economic, social, and environmental point of view.

4.2 Combination of LCA and AHP using Cluster Analysis

The impact points for every scenario are calculated using Eq. (7) in Table 4, and the result is standardized using Eq. (8). The outcome is rated using the scale presented in Table 5 to obtain LCA Environmental Impact (LCA-EI). The concept of cluster analysis is applied using Eq. (9) to map LCA-EI into space as the vertical axis against the economic and social criteria. They are presented in the figure below:

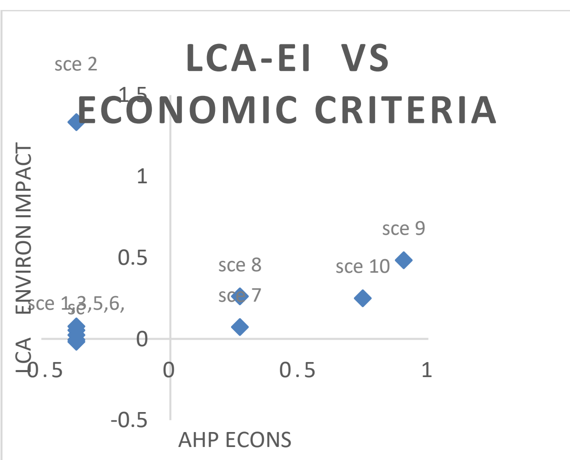


Fig.8.1 LCA EI Versus AHP Economic Criteria

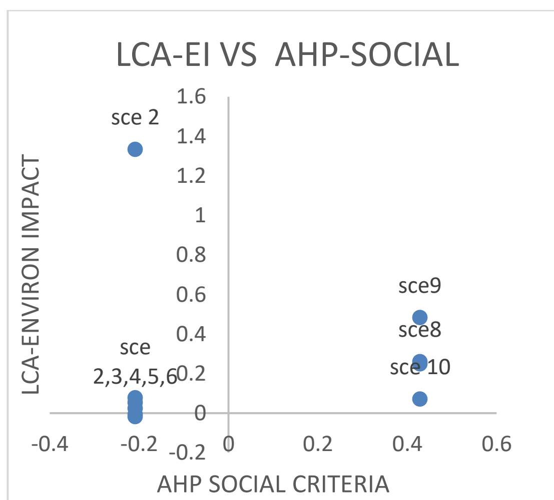


Fig.8.2 LCA EI Versus AHP Social Criteria

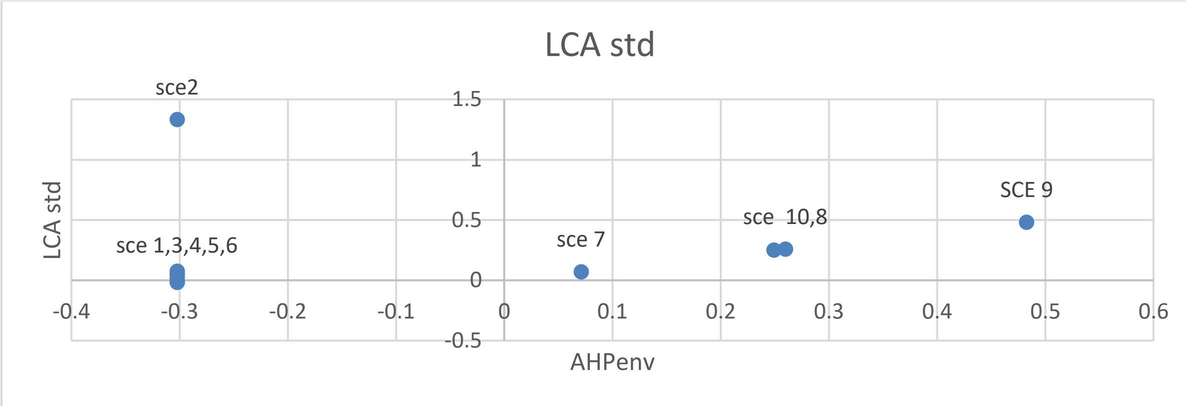


Fig.8.3 LCA EI Versus AHP Environment Criterial

Figure 8.1- 8.3 above shows the performance of the scenarios with respect to economic, social, and environmental perspectives. From the economic perspectives, scenario 9 is the best, followed by scenarios 10, 8, and 7, respectively. Scenario 2 is not desirable, although better than scenarios 1,3,4,5, and 6. From the social perspectives, scenario 9 is the best, followed by scenarios 8 and 10, respectively. Scenario 2 is not good, but it is better than scenarios 1,3,4,5, and 6. From the environmental perspective, scenario 9 is the best, followed by 8, 10, and 7. Scenario 2 is not desirable, but it is better than scenarios 1,3,4,5, and 6. Hence, scenarios 9,10,8 and 7 respectively have consistently emerged from all fronts (social, economic, and environmental). There is a need to test the feasibility of these scenarios with a metric that can assess them from these fronts at once. This brings up the concept of sustainability in WM system designs.

4.3 Overall environmental impacts of the scenarios and the waste treatment technology

The overall view of the environmental criteria and the environmental impact of the waste treatment technology is presented in Figure 9 below.

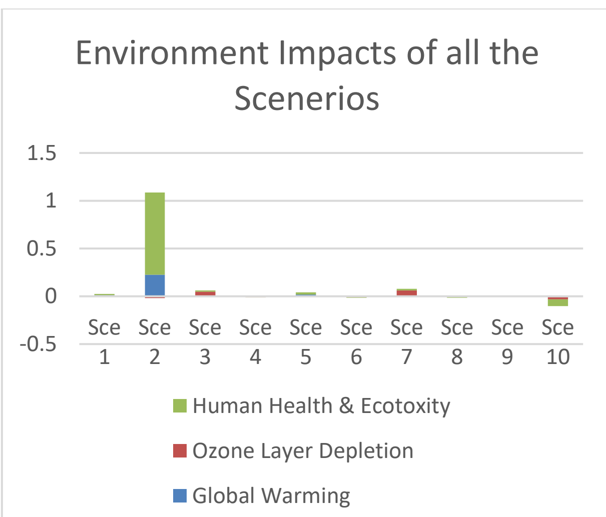


Fig. 9a Overall environmental Impacts across all scenarios

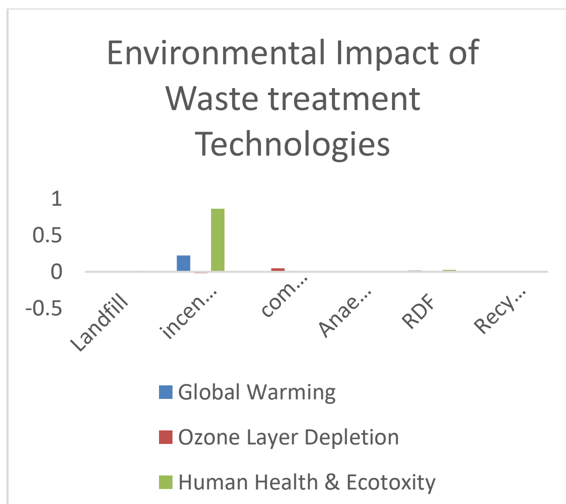


Fig.9b Environmental Impacts of Treatment Technologies

Scenario 2 poses the greatest threat to human health as it unleashes global warming and a very high ecotoxicity on the planet Earth and its inhabitants. Scenarios 9 followed by 8 are the most preferable of the ten scenarios as they are most viable and environmentally friendly. Figure 7b shows that recycling is the best option among the waste treatment technologies, followed by anaerobic digestion, composting, and refuse-derived fuel. Incineration performs the least.

4.4 Comparison of the proposed framework with the existing system

The proposed SISWM is not only desirable and needed but also fits the location, hence satisfying the need on the three aspects of sustainable development for a twenty-first-century global city. The current approach is based on dumping all the waste at any sanitary or unsanitary landfill around and burning any combustible waste beside the house. Based on the peculiarity of the location of the study area and the judgments of various stakeholders involved, the result of scenario analysis favors the proposed SISWM framework presented in Figure 9, with the system boundary presented in Figure 10 below. This hybrid scenario is formed from the combination of scenarios 9 and 10, with 15% of the waste stream recycled,32% treated to anaerobic digestion,20% for composting,7.7% for refuse-derived fuel, 18.3% to an incinerator, and 7.66% sent to landfill. The proportion of waste apportioned to different waste treatment technologies is based on the empirical findings, thus enhancing a viable, equitable, and bearable SWM design.

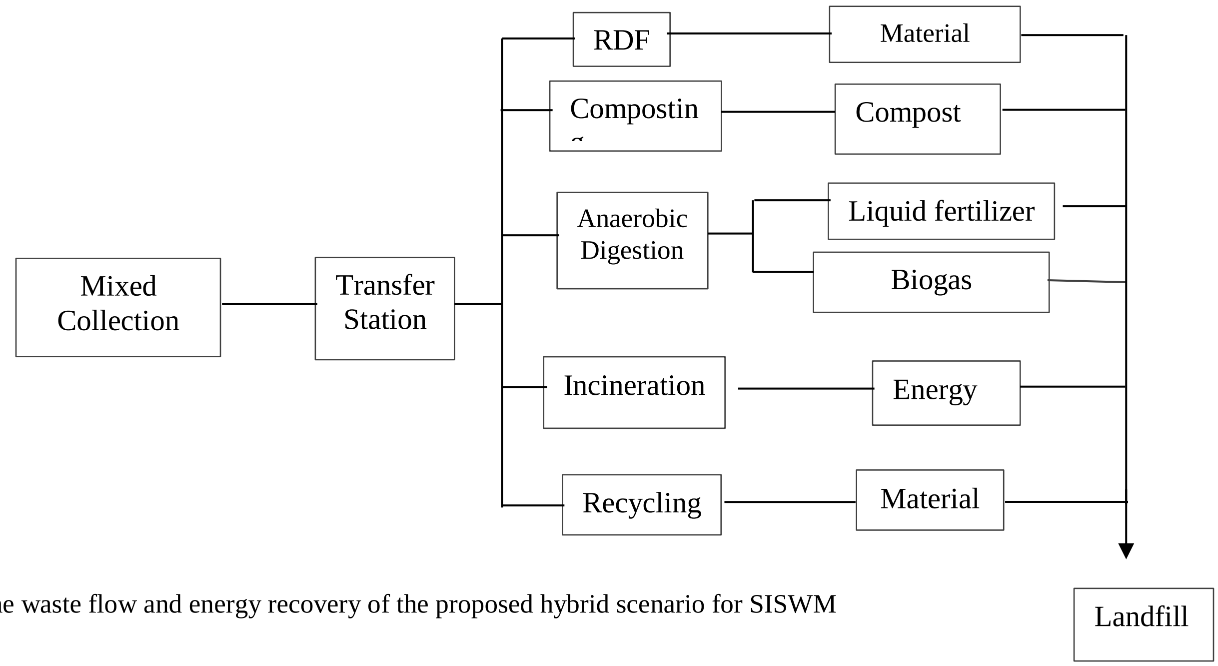


Fig.10: The waste flow and energy recovery of the proposed hybrid scenario for SISWM

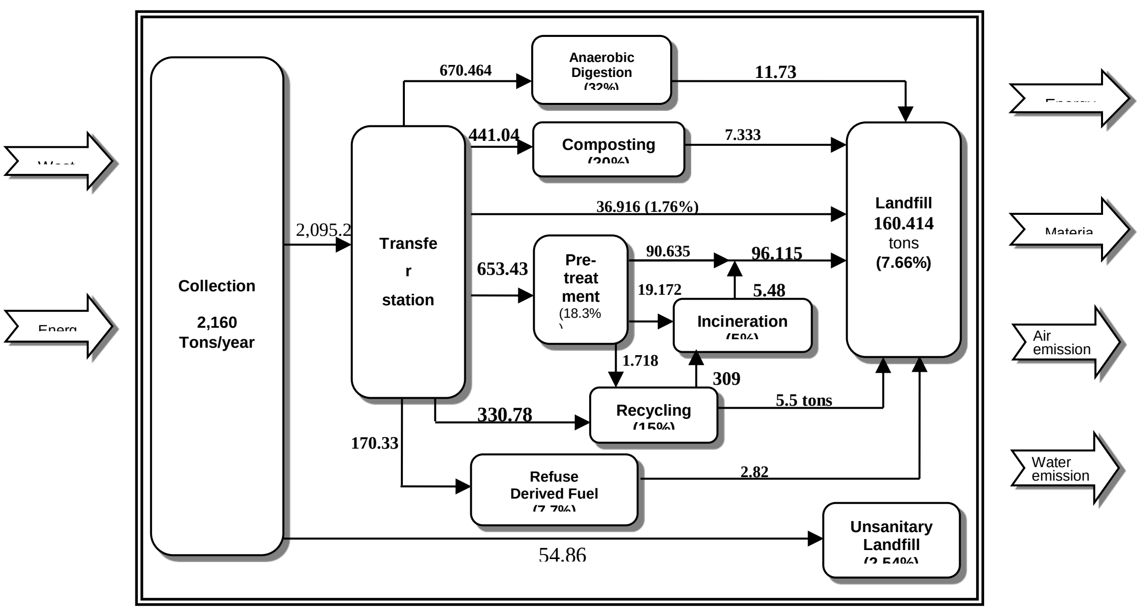


Fig.11: The system boundary for the proposed SISWM

5. CONCLUSION

A sustainable integrated solid waste management framework based on scenario analysis is proposed and described. It has demonstrated the possibility of a waste management system design with facilities like anaerobic digestion, incinerator, material recycling facility, refuse-derived facility, composting facility, and landfill under different scenarios with respect to the prevailing conditions and peculiarity of any location at any point in time. This rating helps the stakeholders to determine the best scenario that favors a given situation, which will achieve the goal without changing some of the key parameters of the metrics. The results of the proposed framework depend on the assumptions made for the decision parameters, such as design cost, set-up cost, operating cost, contribution to gross domestic product, global warming tendency, ozone layer depletion, human health and eco-toxicity, people’s awareness and enlightenment, people's participation, as well as the proximity and alternative land availability for the waste facility. The proposed scenario is a hybrid formed from the aggregation of the two best scenarios (9 and 10). The environmental benefits and the waste volume composition of the hybrid scenario are presented in Figure 11 below. The framework is generic and flexible as it enhances the incorporation of other types of assessments. The proposed framework can be used as a basis for making management decisions, setting targets, and making action plans that enhance a SISWM. There is a need in future work to apply the principle of optimization to the various components and facilities in the waste management designs and metrics.

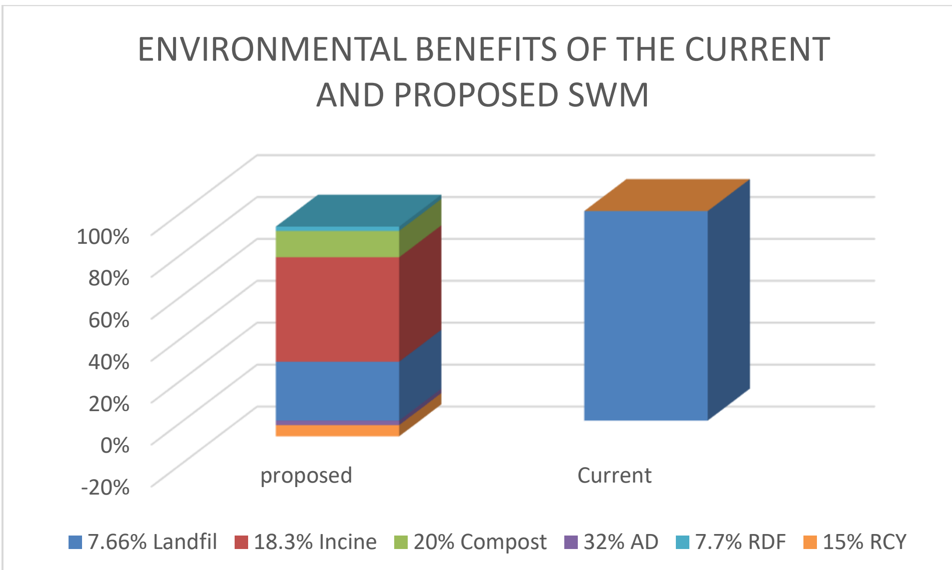


Fig.12: Environmental benefits and waste volume composition for the SISWM

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