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Multiobjective Mathematical Optimization Model for Municipal Solid Waste Management with Economic Analysis of Reuse/Recycling Recovered Waste Materials

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Abstract: Municipal solid waste management in developing countries like Nigeria did not consider benefits from reuse/recycling recovered waste materials during solid waste evacuation and disposal. The benefits from recovered waste materials mostly go to informal waste vendors and scavengers. This study developed a multiobjective mathematical programming model for waste evacuation and disposal, considering the benefits of reuse/recycling recovered waste materials. Data were collected from the Abuja environmental protection board (AEPB), personal interviews, and other stakeholders. The formulated model was solved using spreadsheet solver version 14.0. The study uses various daily budgetary provisions for solid waste evacuation and disposal at a 15% recovery level of solid waste materials to observe the responses of the model. The solution shows that at 71.5% recovery of reuse/recycling recovered waste material; no budgetary provision is required to evacuate and dispose of the waste at the collection centers. Benefits realized from recovered waste materials are sufficient to evacuate and dispose of the wastes. After a 71.5% level of recovery, the net benefit of $1,108.17 from recovered waste materials starts to accrue until the percentage recovery level reaches 100%. The volume of waste shifted to the disposal sites was reduced to 74.5 tons (i.e., unrecoverable waste material) which is 16.82% of the total waste generated per day, and 368.33 tons (83.18%) of waste materials were recovered. The study will give the policymakers viable information to aid proper planning while budgeting and controlling solid-waste-associated problems in the Abuja municipal area in particular and the country as large.

Keywords: multiobjective mathematical optimization model, goal programming model, economic benefit, reuse/recycling recovered waste materials, budgetry provision, Abuja, Nigeria

1. Introduction

Municipal solid waste (MSW) includes any discarded unwanted material that is not liquid or gaseous. It comes from everyday product packaging, grass clippings, street sweeping, demolition and construction of buildings, clothing, discarded furniture, cans and bottles, newspapers, food scraps, electronics, and batteries. These wastes are generated mainly from homes, institutions such as agencies, schools, and commercial sources such as motor packs, restaurants, and small businesses (Peter, 1996; US Environmental Protection Agency, 2016).

Before the 1970s, management of MSW generally consisted of depositing the wastes in open or excavated landfills, accompanied by open burning to reduce waste volumes. The method is associated with many environmental problems, such as groundwater contamination, toxic fumes and greenhouse gas (GHG) emissions, land contamination, and increases in pest and disease vector populations (e.g., rodents, flies, and mosquitoes) (US Environmental Protection Agency, 2016). Other MSW management methods include source reduction, recycling, composting, incineration, etc. Solid waste management is also a process that involves activities of collection, source separation, storage, transportation, transfer, processing, treatment, and disposal of discarded solid waste material in an environmentally sustainable manner (Ahsan et al., 2014; Demirbas, 2011; Ding et al., 2021; Ravindraet et al., 2015; Williams et al., 2008). Improper management of MSW causes a hazard to inhabitants. Management of MSW is a significant problem in urban centers of developing countries due to continuous increase in the volume of waste due to rise in income, population growth, and urbanization (Khanlari et al., 2012). It is one of the challenging issues in our urban centers due to various interrelated factors such as operational cost and environmental issues; it continues to be a big challenge in urban centers of developing countries (Asefi et al., 2015; Sabeen et al., 2016).

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Due to limited resources, proper management and control of these wastes have become a dilemma. Most of the agencies face a limited budgetary provision for solid waste management. In developing countries, the situation is acute due to rapid urbanization, uncontrolled population growth rate, and little financial commitment (Sarika, 2007; Sunil, 2005). Various studies reveal that about 90% of MSW is disposed of unscientifically in open dumps, open burning, and landfills in developing countries, creating problems to public health and the environment (Sharholy et al., 2008).

Municipal solid waste contains not only "valuable" but also recycling and reusable material such as metal, glass, paper, plastics, etc., which in many cases are unrecovered during the waste management process. In most cases, the recovery of recoverable waste material is not formal, mostly carried out by scavengers and informal waste vendors (Barma et al. 2014). A complex network approach has been adopted to manage municipal waste in Italy (Cerqueti et al., 2021). The study analyzed the wastes separation percentages at the level of municipality, and studied the municipal distance role from plants in the waste management network.

Researchers used several mathematical approaches to various model activities of the solid waste management system in areas such as solid waste generation prediction, minimization of volume of waste generated, optimization of waste facilities operation, facility site selection, optimal routing of waste transport vehicle in the waste management system, etc. (Nganda, 2007; Prawiradinata, 2004). According to Yousefloo and Babazadeh (2020), the high rate of people influx into capital cities gave birth to the increase of waste production and hence the need for policymakers to manage such wastes for proper town planning of the scarce resources. They proposed a bilevel multiobjective mixed-integer linear programming (MILP) model for designing and planning of MSW network considering outsourcing via auctions. A sustainable MSW network has been designed and studied under uncertainty (Mamashli & Javadian, 2021). The study analyzed associated location risk based on the case study population. Similarly, MSW disposal rates have been modelled during the COVID-19 pandemic using the waste fraction separation model (Vu et al., 2021). Ghosh et al. (2021) viewed the MSW problem from socio-ecological and techno-managerial perspectives and applied an artificial neural network to assess the situation in two different municipalities.

Most studies on solid waste management did not consider the economic benefits of recycling/reuse recovered waste materials during solid waste management. Several deterministic mathematical programming models have been used for planning and controlling solid waste management systems. Peirce et al. (1982) applied linear programming techniques to identify a cost-effective configuration of transportation routes, transfer stations, processing facilities, and long-term storage impoundments for hazardous waste management. The model gives optimal routes for the given structures of hazardous waste management facilities. Rakas et al. (2004) have developed a multiobjective model for determining locations of undesirable facilities with conflicting criteria. The designed model helped address critical questions, such as how many facilities locations are needed, how large each facility should be and so on. Alidi (1996) proposes a multiobjective optimization model using a goal programming approach to manage hazardous waste generated by the petrochemical industry properly. Chang et al. (2012) studied MSW management integrating cost–benefit criteria and global warming potentials for optimal planning of the SWM system in Pennsylvania. The study estimated greenhouse gas (GHG) emissions and optimizes the net benefits, prioritizing the options for materials recovery facilities before the waste disposal process. Several researchers applied the optimization models, particularly goal programming and its variants, in studying socio-economic problems related to environmental sustainability (Ahmadini et al., 2021; Modibbo et al., 2021; AlArjani et al., 2021; Khan et al., 2021).

Multiobjective mathematical programming has been adopted in improving policy performances on sustainable MSW management strategies in Italy (Cucchiella et al., 2014). The study quantifies and evaluates the effects of the new waste diversion policy from landfills and uses economic indicators to define Italy's waste facilities profitability. Asefi and Lim (2017) considered the economic, environmental, and social factors in developing reliable and sustainable indicators for integrated MSW management using multicriteria decision-making (MCDM) techniques. The study incorporates the ε-constraint method to maximize the system suitability and minimize the transportation and fixed costs of the MSW system in Tehran. Waste generation has been modeled recently using technology-specific bases due to the growing demand for waste disposal capacity and recycling for future consumption (Chen et al., 2021).

Recently, the MSW network and its potential destinations have been optimized using the MILP approach considering landfilling and waste reduction process (Garibay-Rodriguez et al., 2018). Also, an MILP model has been developed considering CO_2 emissions and water consumption in a study on sustainable agricultural supply chain networks using the concept of hybrid meta-heuristics algorithms (Goodarzian et al., 2023). Awasthi et al. (2018) have modeled the correlation between e-waste and gross domestic products. Puchongkawarin and Mattaraj (2020) use superstructural optimization to develop a decision-making tool for the optimal design of MSW facilities in Thailand. They formulated the problem as an MILP to maximize the profit under uncertainty. Similarly, Tsai et al. (2020) conducted a comparative study for the MSW management attributes in different cities of Vietnam under uncertain environments. The study identified 14 features and used the DEMATEL technique to evaluate the causal relationships from different towns. Gu et al. (2021) considered various MSW separation and compositions sources that impact energy recovery potentials from incineration in Beijing. They used a differential equation model to predict the volume of MSW generation in 2025 to reach 11,505,400 tons with a 2.255% "mean absolute percentage error".

Among the several methods of MSW management, this study considered reuse/recycling methods as one of the most effective, affordable, and sustainable strategies for solid waste management in Nigeria. Therefore, the study developed a multiobjective mathematical programming model to minimize generated volume of solid waste at waste collection centers and disposal sites. The study considered the economic benefit from the reuse/recycling of recovered waste material. The relative importance of the collection centers during waste evacuation and disposal, which is the standard practice, was also considered. Abuja (Nigeria) municipal area was considered as the study area.

The paper is arranged as follows: Section I presents the introduction and discusses related work in MSW management and the techniques used. In Section II, the methodology of this study is presented. The MSW management conceptual framework was designed, model assumptions, nomenclature defined, and finally, the mathematical model of the problem formulated. Section III discusses the method of data collection for the study. In Section IV, model implementation and the study area are discussed with the map showing locations of the various wastes management facilities. Section V discusses the model results, analysis, findings, and managerial implications. The article concludes in Section VII with future scope for possible exploration.

2. Material and Methods

The mathematical programming approach is a valuable technique in optimizing the MSW management system, evident from the above-reviewed literature. One of such techniques is goal programming (GP). A typical mathematical programming model can be formulated as follows:

$$\left.\begin{array}{l}\text{Optimize } Z(X)\\ \textit{Subject to}:\\ \qquad g_i(x)(\leq,=,\geq)b_i\\ \qquad x_i\geq 0; i=1,2,\ldots,\text{n}\end{array}\right\} \quad (1)$$

Where g_i are the set of constraints with b_i as available resources, and Z is the objective function with X the set of decision vectors. Equation (1) can be minimization or maximization in nature and can have single or multiple objectives. The constraints equation can take any form of the inequalities depending on the problem type and nature. The optimization model (1) has several variants depending on the nature of the problem. The algorithm is one of the MCDM techniques in which decision problems with several conflicting criteria are considered (Hung et al., 2006; Minciardi et al., 2008). In this study, MSW management with reuse/recycling recovered waste material was structured as a multiobjective decision-making (MODM) problem. The MODM problem can be divided into three parts: preference, interactive, and nonpreference type (lexicographic, multiattribute utility, and unknown utility) (Hung et al., 2006). The interactive multiobjective decision making mathematical programming approach was adopted based on WGP.

2.1. Weighted goal programming technique

The WGP is one of the GP variants, and this study considered the algorithm in developing the MSW management model in this study. The method involves determining the relative importance of the attributes and aggregating them into some kind of overall objective. The optimization problem is solved to generate the optimal solution for a given set of attributes. The method weighs the objectives to obtain Pareto optimal solutions. Each objective incorporates user-supplied weights based on their relative importance and sums up to give a single objective to be minimized.

Let the weighted model of a multiobjective optimization problem with k objectives be given as follows:

$$\left.\begin{array}{l}\text{Min}: Z(X)=\sum_{i=1}^{k} w_i f_i(x)\\ \textit{Subject to}:\\ \qquad x\in S\\ \qquad \sum_{i=1}^{k} w_i=1\\ \qquad w_i\geq 0; i=1,2,\ldots,k\end{array}\right\} \quad (2)$$

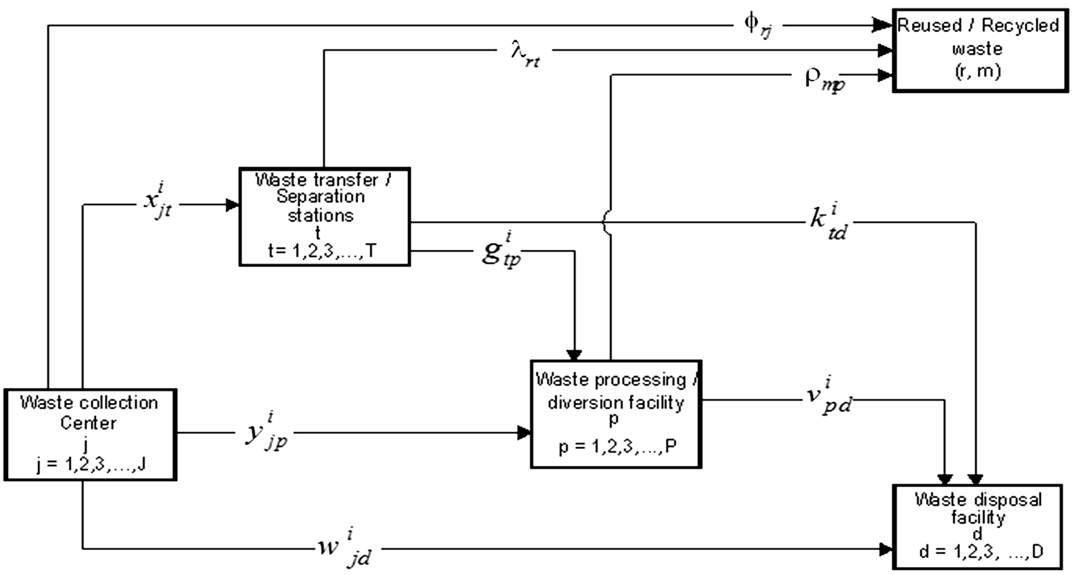
Where $Z(X)$ denotes the objective functions, X represents the sets of decision variables, and S represents the sets of constraints. Any set of nonnegative weights w_i may be used in equation (2). However, without loss of generality, we can normalize all weights such that $\sum_{i=1}^{k} w_i = 1$.

Suppose the optimization problem in equation (2) has a single objective. In that case, it can be solved by existing methods such as the graphical method (applied to two variables problems), sequential goal programming method, and multiphase simplex method (Hung et al., 2006). The conceptual framework of the model is given in Figure 1.

2.2. Description of conceptual framework representation of the waste flow

Figure 1 represents the network flow of waste from the collection centre $j(j = 1,2,3,\ldots,J)$ to the final disposal facilities sites $d(d = 1,2,3,\ldots,D)$ in the MSW management system. Between the collection points and the disposal facilities are waste transfer stations $t(t = 1,2,3,\ldots,T)$ and various waste processing/diversion facilities $p(p = 1,2,3 \ldots, P)$. The flow of wastes of type i from waste collection point j to a particular transfer station t, processing/diversion facility p, and disposal facility d (residual) is represented by $x^i_{jt}, y^i_{jp}, w^i_{jd}$. The flow of wastes of type i from a

Figure 1
Conceptual framework of the solid waste management system



particular transfer station t to a particular processing/diversion facility ρ and disposal facility d is represented by g^i_{tp} and k^i_{td}, respectively. The flow of volumes of residues from processing/diversion facility ρ to disposal facility d, when the processing/diversion facility processes waste type i, is represented by v^i_{pd}. The flow of fractional amount of recovered material r to the market from the collection center j is represented by ϕ_{rj}. The flow of fractional amount of material r to the market from transfer station t is represented by λ_{rt}. The flow of fractional volumes of recovered material m (reuse/recycling waste materials, compost material, refuse-derived fuel, etc.) to the market from the processing/diversion facility p is represented by ρ_{mp}. Waste collection center—the generated wastes are collected at point sources representing neighborhoods referred to as waste collection centers, depots, or refuse dumpsites. This enables generated wastes from a different household cluster to gather their waste in one place for accessible collection by smaller trucks to various waste management facilities. Transfer stations—These are centralized facilities where waste from a cluster of collection centers is unloaded from smaller collection trucks (containers) and reloaded into larger vehicles for transportation to other facilities in the waste management system (Environmental Impact Assessment, 2010). Waste processing and diversion facilities—the waste processing activities deal with the recovery of waste material and recycling activities.

Meanwhile, waste diversion deals with the transformation of solid waste through combustion or incineration, treatment, and composting. The waste processing/diversion facilities tend to reduce the volume of waste flows to disposal facilities. Sorted/separated waste may come from waste collection centers, transfer stations, or waste processing/diversion facilities. At these facilities, recovered/recycled waste materials are sent to the market, unrecovered but transformed waste (residue) are then sent to the disposal facilities. Disposal facilities—The last option in the SWM system is the final disposal of the waste; this is the final destination of the wastes that are not recovered. A standard method of final disposal of solid waste, mostly in use, is sanitary landfilling (Kreith, 1994; Zerbock, 2003).

2.3. Model assumptions

For any mathematical model, there are assumptions under which the model can be formulated. The following are the assumptions in the present study:

i. Wastes generated in each community are collected at designated collection centers.
ii. Waste at collection centers is only moved to the transfer station facility, processing/diversion facility, or disposal site base on policy directives.
iii. All waste management facilities have a percentage level of recovery for the various recovered waste materials except for disposal sites.
iv. There is market value for reused/recycled waste material.

2.4. Model parameters

μ_j = The amount of wastes at the collection center j.

Γ_t = Capacity of waste transfer station facility t

$\prod_p$ = Capacity of waste processing/diversion facility p

Ω_d = Capacity of waste disposal facility d.

a^i_{jt} = Cost of transportation per unit waste of type i from collection center j to transfer station facility t.

b^i_{jp} = Cost of transportation per unit waste of type i from collection center j to processing facility p

c^i_{jd} = Cost of transportation per unit waste of type i from collection center j p to disposal facility d.

n^i_{tp} = Cost of transportation per unit waste of type i from transfer station t to processing facility

q^i_{td} = Cost of transportation of unit waste of type i from transfer station t to disposal facility d.

u^i_{pd} = Cost of transportation of residue from processing facility p to disposal facility d when waste type i is processed.

γ^i_j = Cost of handling per unit waste of type i at collection center j.

A^i_t = Cost of handling per unit waste of type i at transfer station facility t.

θ_r = Percentage of material r in the waste.

ϕ_{rt} = Percentage of reused/recycled material r can be recovered at collection center j.

λ_{rt} = Percentage of reused/recycled material r can be recovered at transfer station t.

p_{mp} = Percentage of recovered material m at processing/diversion facility p.

Ψ_r = Per unit revenue (or benefit) of recycle/reused material r.

ψ_{mp} = Per unit revenue (or benefit) of recovered material m at processing/diversion facility p.

α = Percentage of waste from collection centers moved to transfer stations.

π = Percentage of waste from collection centers moved to processing facilities.

η_{tp} = Percentage of waste moved from transfer station t to processing facility p.

B = Budgetary allocation for waste management operation for a defined period.

$T_{NetCost}$ = Total net cost of solid waste management.

2.5. Model nomenclature

x^i_{jt} = Amount of waste type^i moved from waste collection center j to waste transfer station facility t

y^i_{jp} = Amount of waste type i moved from waste collection center j to waste processing facility p

w^i_{jd} = Amount of waste type i moved from waste collection center j to waste disposal facility d

g^i_{tp} = Amount of waste type i moved from the waste transfer station t to waste processing facility p

k^i_{td} = Amount of waste type i moved from waste transfer station facility t to waste disposal facility d

v_{pd} = Amount of residue moved from waste processing/div. facility p to waste disposal facility d

$\tau^i_{jt} = 0$ indicates waste of type i from collection center j cannot be moved to a transfer station t.

$\tau^i_{jt} = 1$ indicates waste of type i from collection center j can be moved to a transfer station t.

$\delta^i_{jp} = 0$ indicates waste of type ^{i} from collection center j cannot be moved to a processing/diversion facility p

$\delta^i_{jp} = 1$ indicates waste of type ^{i} from collection center j can be moved to processing/diversion facility p

$\varsigma^i_{jd} = 0$ indicates waste of type i from collection center j cannot be moved to a disposal facility d

$\varsigma^i_{jd} = 1$ indicates waste of type i from collection center j can be moved to a disposal facility d

$h^i_{tp} = 0$ indicates waste of type i from transfer station t cannot be moved to processing/diversion facility p

$h^i_{tp} = 1$ indicates waste of type i from transfer station t can be moved to processing/diversion facility p

$e^i_{td} = 0$ indicates waste of type i from transfer station t cannot be moved to a disposal facility d

$e^i_{td} = 1$ indicates waste of type i from transfer station t can be moved to a disposal facility d

$l^i_{pd} = 0$ indicates residue from waste of type i from processing/diversion facility p cannot be moved to disposal facility d

$l^i_{pd} = 1$ indicates residue from the waste of type i from processing/diversion facility p can be moved to a disposal facility d

s^{j-}_1 = Amount of waste not removed from the collection center j

s^+_2 = The additional required amount of money in the waste management operation for the defined period.

s^-_2 = The amount of money remained after waste management operation for the defined period.

2.6. Model formulation

Here, the above-defined parameters and nomenclature incorporating the assumptions are considered to formulate the mathematical model for solid waste evacuation and disposal with economic benefits from recovered waste materials and the relative importance of collection centers. The model is formulated as a weighted goal programming where the deviations from the target goals are minimized as the objective function—subjected to some constraints.

$$Minimize: \ Z = \sum_{j=J} \omega^{j-}_1 s^{j-}_1 \tag{3}$$

Subject to

$$\sum_{i\in J}\sum_{t\in T} x^i_{jt}\tau^i_{jt} + \sum_{i\in I}\sum_{p\in P} y^i_{jp}\delta^i_{jp} + \sum_{i\in I}\sum_{d\in D} w^i_{jd}\varsigma^i_{jd} + s^{j-}_1 = \mu\left(1 - \sum_{r\in R}\phi_{rj}\theta_r\right), \quad \forall j \tag{4}$$

$$\sum_{j\in J}\left(\sum_{i\in I}\sum_{t\in T} x^i_{jt}\tau^i_{jt} + \sum_{i\in I}\sum_{p\in P} y^i_{jp}\delta^i_{jp} + \sum_{i\in I}\sum_{d\in D} w^i_{jd}\varsigma^i_{jd}\right) = \sum_{j\in J}\mu_j\left(1 - \sum_{j\in J}\phi_{rj}\theta_r\right), \tag{5}$$

$$\sum_{i\in I}\sum_{j\in J}\left[x^i_{jt}\tau^i_{jt}\left(1 - \sum_{r\in R}\lambda_{rt}\theta_r\right)\right] - \sum_{i\in I}\sum_{p\in P} g^i_{tp}h^i_{tp} - \sum_{i\in I}\sum_{d\in D} k^i_{td}e^i_{td} = 0, \quad \forall t \tag{6}$$

$$\sum_{i\in I}\sum_{j\in J}\left[y^i_{jp}\delta^i_{jp}\left(1 - \sum_{m\in M}\rho_{mp}\right)\right] + \sum_{i\in I}\sum_{t\in T}\left[g^i_{tp}h^i_{tp}\left(1 - \sum_{m\in M}\rho_{mp}\right)\right] - \sum_{i\in I}\sum_{d\in D} v^i_{pd}l^i_{pd} = 0, \quad \forall p \tag{7}$$

$$\sum_{i\in I}\sum_{j\in J} x^i_{jt}\tau^i_{jt} \ \le \ \Gamma_t, \quad \forall t \tag{8}$$

$$\sum_{i\in I}\sum_{j\in J} y^i_{jp}\delta^i_{jp} + \sum_{i\in I}\sum_{t\in T} g^t_{tp}h^i_{tp} \le \Pi_p, \quad \forall p \tag{9}$$

$$\sum_{i\in I}\sum_{j\in J} w^i_{jd}\varsigma^i_{jd} + \sum_{i\in I}\sum_{t\in T} k^i_{td}e^i_{td} + \sum_{i\in I}\sum_{p\in P} v^i_{pd}l^i_{pd} \le \Omega_d, \quad \forall d \tag{10}$$

$$\sum_{i\in I}\sum_{j\in J}\sum_{t\in T} x^i_{jt}\tau^t_{jt} - \alpha\sum_{j\in J}\left(\sum_{i\in I}\sum_{t\in T} x^i_{jt}\tau^t_{jt} + \sum_{i\in I}\sum_{p\in P} y^i_{jp}\delta^i_{jp} + \sum_{i\in I}\sum_{d\in D} w^i_{jd}\varsigma^i_{jd}\right) \ge 0 \tag{11}$$

$$\sum_{i\in I}\sum_{j\in J}\sum_{p\in P} y^i_{jp}\delta^i_{jp} - \pi\sum_{j\in J}\left(\sum_{i\in I}\sum_{t\in T} x^i_{jt}\tau^i_{jt} + \sum_{i\in I}\sum_{p\in P} y^i_{jp}\delta^i_{jp} + \sum_{i\in I}\sum_{d\in D} w^i_{jd}\varsigma^i_{jd}\right) \ge 0 \tag{12}$$

$$\sum_{i\in I}\sum_{p\in P}\sum_{t\in T} g^i_{tp}h^i_p - \eta\sum_{i\in I}\sum_{t\in T}\sum_{j\in J}\left[x^i_{jt}\tau^i_{jt}\left(1 - \sum_{r\in R}\lambda_{rt}\theta_r\right)\right] = 0 \tag{13}$$

$$T_{NetCost} + s^-_2 - s^+_2 \ = \ B \tag{14}$$

$$\sum_{j\in J}\omega^{j-}_1 \ = \ 1, \quad \omega^{j-}_1 \ge 0 \tag{15}$$

$$\tau^i_{jt}, \delta^i_{jp}, \varsigma^i_{jd}, h^i_{tp}, e^i_{td}, l^i_{pd} = [0, 1] \tag{16}$$

$$x^i_{jt}, y^i_{jp}, w^i_{jp}, g^i_{tp}, k^i_{td}, v^i_{pd} \ge 0, \ i = 1, 2, \ldots, I; \ j = 1, 2, \ldots, J; \ t = 1, 2, \ldots, T; \ p = 1, 2, \ldots, P; d = 1, 2, \ldots, D \tag{17}$$

$$s^{j-}_1, s^{\pm}_2 \ \ge \ 0, \quad j = 1, 2, \ldots, J$$

3. Input Data

Data on MSW management in most urban centers of developing countries are relatively unavailable compared with developed countries (Ogwueleka, 2009). Personal interview was used to obtain relevant data from stakeholders. Data for the study were collected from Abuja Municipal Area SWM Agency (AEPB), and other stakeholders such as private sectors/wastes management contractors and NGOs. Data were also collected from some selected community members (Abuja residents) and concerned resource personnel in the waste management Agency- AEPB. Face-to-face interviews were used to collect data from the Budget and Finance Department of AEPB. Data on types of waste were generated, and the quantity of waste generated in Abuja Municipal Area was obtained from the department of solid wastes management of AEPB.

Preliminary field investigation/observation was carried out to understand the existing solid waste management methods in practice. The preliminary field survey was also conducted to ascertain waste collection centers, waste transfer stations, waste processing, and disposal facilities. Volumes of wastes generated from various waste collection centers and capacities of waste management facilities were obtained from the records of the waste management department of the agency-AEPB and Abuja waste management contractors.

The various waste management costs were obtained from the Abuja waste management contractors, wastes pikers, informal wastes vendors, wastes scavengers, and other interest groups and individuals (Abuja residents). They include fixed cost, transportation cost, waste processing cost, material recovery cost, and revenue from recovered waste material.

The fixed costs include the cost of acquiring the land and the cost of obtaining waste management types of equipment and tools. The transportation cost is the cost of moving the waste between various facilities in the waste management system.

The processing cost is related to waste handling costs at various facilities. Waste materials' recovery cost is the recycled/reused waste

Table 1
Waste type and percentage of waste type in Abuja municipal area

S/No.	Waste Types	Percentage of Waste Type
1	Organic matters	45.88
2	Paper waste	12.56
3	Nylon waste	11.56
4	Cardboards	7.56
5	Plastic waste	6.69
6	Metals	3.3
7	Glass/bottles	2.81
8	Textiles waste	2.67
9	Misc. combustible	3.22
10	Misc. noncombustible	2.03
11	Electronic waste (e-waste)	1.24
12	Nonferrous metals	0.48
Total		**100**

Source: Waste audit report by resource recovery unit, AEPB, 2010.

material type per ton in the waste stream. Revenue is the amount realized on the sale per ton of the recovered waste materials.

Percentage compositions of the various waste and waste materials that can be recovered were obtained from the records of the waste management department of the agency and other previous works (Ayuba et al., 2013). The cost of recovery of materials and the value of the recovered materials were estimated from informal waste vendors. The percentage levels of recovery of the various reuse/recycle waste materials in the various facilities were estimated through interaction with experts in the waste management department of AEPB and informal waste management vendors.

Criteria used during solid waste evacuation and disposal in the collection centers were obtained from the Agency-AEPB. Pairwise comparisons of the criteria and pairwise comparisons of the collection centers concerning the criteria were carried out with the agency's representatives. The nine-point numerical rating scale of Analytical Hierarchy Process (AHP) (Bhushan & Rai, 2004; Saaty, 1990; Tarmudi et al., 2010) was used to determine the relative importance (priority weights) of collection centers.

Table 1 shows the waste type and composition of the waste at Abuja municipal area. In contrast, Table 2 shows the amount of waste in tons per month and per day in the collection centers.

4. Study Area and Model Implementation

Abuja is the capital city of Nigeria. The city is located at the country's geographical center approximately at latitude 9°12′ north of the equator and along longitude 7°11′ east of the Greenwich Meridian (Adama, 2007). It has an estimated population of 1.4 million people, of which 405,000 live and work within the municipality (National Population Commission, 2008). It has a total land area of approximately 713 km^2 divided into six area councils, namely Abuja Municipal, Abaji, Bwari, Gwagwalada Kuje, and Kwali. The climate is generally tropical, and it has tropical, mainly savannah vegetation except for the southern fringes covered by secondary rainforest vegetation. Total annual rainfall in the city averages 1100 mm. The city is located in a scenic valley of rolling grasslands in a relatively undeveloped, ethnically neutral area. Its planners hoped to create a national city where none of Nigeria's social and religious groups would be dominant (Ezeah & Roberts, 2012; Oyeniyi, 2011).

The Government institution responsible for solid waste management in the City (Abuja Municipal) is the AEPB (Adama, 2007). The Board's solid waste management portfolio has the following components: City cleaning (concessioned to local contractors in a public–private participation arrangement), street sweeping, litter control, solid waste collection, transfer and vegetation control, management of the garden, hospital, and waste evacuation. Protection and improvement of air, water, land, forest, wildlife and ecological quality, pollution control, and environmental health services are also among its mandates (Akoni, 2007). Therefore, MSW management is one of the central mandates of the Board. AEPB solid waste department is responsible for the collection, transfer, waste disposal, and waste material procurements and distribution in the city.

4.1. Abuja municipal area solid waste management system

The Abuja municipal council is divided into 13 waste management areas (waste collection area or district). These collection centers are:: Garki 1, Wuse 1, Wuse 2, Central Area, Gwarinpa, Maitama, Asokoro, Jabi, Durimi, Lugbe, Life Campe, Kado, and Wuye (Figure 3). Each of these areas is a concession to a private subcontractor in contract arrangement. Within the contract period, all operational responsibility for the given area rests on the subcontractor while the AEPB assumes a supervisory role. The contractors collect the waste at various collection points

Table 2
Amount of waste in tons per month, per day in the collection centers

S/No. (j)	Waste collection centers	Amount of waste/Month	Amount of waste/day μ_j
1	Garki I	872.36	29.80
2	Garki II	1,546.28	51.55
3	Wuse I	1,799.00	60.00
4	Wuse II	1,952.50	65.09
5	Central Area	924.77	30.83
6	Gwarinpa	864.87	28.83
7	Maitama	1,097.00	36.57
8	Asokoro	1,583.72	52.79
9	Jabi/Utako/Mboci	1,235.52	41.19
10	Durumi/Gudo/Apo	584.07	19.47
11	Lugbe	284.55	9.46
12	Kado	309.26	10.31
13	Wuye	208.08	6.94
Total		**13,261.98**	**442.83**

Source: Average Monthly collection of a waste report by contractors, AEPB, 2010.

in the respective area. The waste is not categorized or classified at the collection centers or transfer stations. However, some types of wastes were piked by wastes pikers, wastes scavengers, and other individuals. The waste collection is carried out daily for most of the collection areas using compacting trucks, side loaders, open tippers, payloaders, roll-on roll-off trucks, etc. There is one recycling facility at Mpape and two transfer stations at Kubwa and Gudu. Abuja municipality has two waste disposal sites located at Gosa and Ajata, a few kilometers from the city.

4.2. Waste transfer stations

There are two wastes transfer stations, at Kubwa and Gudu. Kubwa transfer station is located along Kubwa expressway, and Gudu transfer station is situated in the center of the city, close to Garki II. Wastes move to these transfer stations from collection centers that are very close to them. Wastes from these transfer stations are later moved to recycle facility at mapped and disposal facilities at Goza and Ajata for the final disposal of the wastes.

4.3. Waste processing facility

The waste processing facility present during this study is the Mpape recycling plant. Wastes come into this plant from collection centers and transfer stations at Kubwa and Gudu. The primary activities in this plant are sorting recycled/reused materials. Some of the recycled/reused materials recovered in these facilities include plastic waste, glass, bottles, electronic waste, polythene bags, metals, woods, and textiles waste. The recycled materials are then taken to some bigger plants in Kaduna, Kano, and Lagos for further processing. Waste vendors informally do these.

4.4. Waste disposal site

Abuja municipality has two waste disposal sites located at Gosa and Ajata, a few kilometers from the city. All the unrecovered wastes from the collection areas, transfer stations, and recycling facility are taken to one of these disposal sites daily. Three methods of waste disposal in practice at the disposal sites are uncontrolled open dumping, uncontrolled open burning, and not engineered landfilling. Worldwide scientific research has conclusively demonstrated that the burning of waste produces air toxins. The amount of these toxins depends on the composition of the waste (Saskatch Ministry of Environment, 2010). Uncontrolled open dumping and not engineered landfill give rise to the emission of gases and produce leaching effect.

4.5. The map of the study area

Figure 2 shows the study area map (Abuja municipal area council). Figure 3 is a map of the study area showing where the wastes evacuation and disposal activities take place with the location of the various wastes management facilities.

5. Results Analysis and Discussion

Multiobjective mathematical programming specifically the WGP models for waste evacuation and disposal with benefits from reuse/recycling recovered waste materials, with comparable importance of collection centers, was developed during waste collection. A model spreadsheet was constructed, and Microsoft Excel Solver version 14.0 was used to solve the problem. Initial budgetary provision of 625.97 USD, and the fixed cost of waste evacuation and disposal, was considered. Incremental budgetary provisions of 1,215.01 USD at the interval were then used to see the responses of the model. AEPB daily budgetary provision (12,097.16 USD) for solid wastes evacuation and disposal in Abuja municipal area was then considered to solve the problem.

The model was then solved for the various budgetary provisions at a 15% level of recovery of reuse/recycle recovered waste materials. Table 3 summarizes the waste evacuation achieved in the diverse collection centers for the budgetary provisions. In contrast, Table 4 summarizes amounts of wastes at disposal sites, amounts of reuse/ recycling recovered waste materials, and the values of the objective function (z) of the model for the various budgetary provisions. For example, a fiscal provision of 625.97 USD (row 1 of Table 3) shows that all the wastes in collection centers 1 and 2 were evacuated, and 17.97 tons out of 58.83 tons of wastes were removed from collection center 4. The zero entries in the collection centers (2, 5, 6, 7, 8, 9, 10, 11, 12, and 13) show that no waste is removed in those collection centers as indicated by the values of underachievement deviation variables s_1^{j-}, *for* $j = 2, 5, 6, 7, 8, 9, 10, 11, 12, 13$ (see Table 5- excel solver solution).

With 2,430.02 USD budgetary provisions, all the wastes at collection centers 1, 2, 3, 4, and 11 were evacuated entirely (see Table 3, row 3). Similarly, out of 27.78 and 47.71 tons of wastes at the collection centers, 5 and 8, 5.40 and 39.44 tons were evacuated. The values of the decision variables $x_{31}, x_{41}, x_{21}, x_{11}, x_{41}, x_{51}, x_{81}$, and $w_{11,1}$ indicated the information (see Table 6—excel solver solution). Row 3, column 3 of Table 4 shows the total amount of wastes evacuated in the collection centers as 239.97 tons. Row 11 of Tables 3 and 4 shows the solution obtained from the agency (AEPB) daily budgetary provision (12,097.16 USD). It indicates that all the wastes at the collection centers were evacuated, as shown by the value of underachievement deviational variables $s_1^{j-} = 0.00$, *for* $j = 1, 2, \ldots, 13$ and objective function value $z = 0.00$ (Table 7—excel solver solution). The total amount of 6,496.71 USD was left unused. It is about 54% of the total daily budgetary provision by the agency for waste evacuation and disposal.

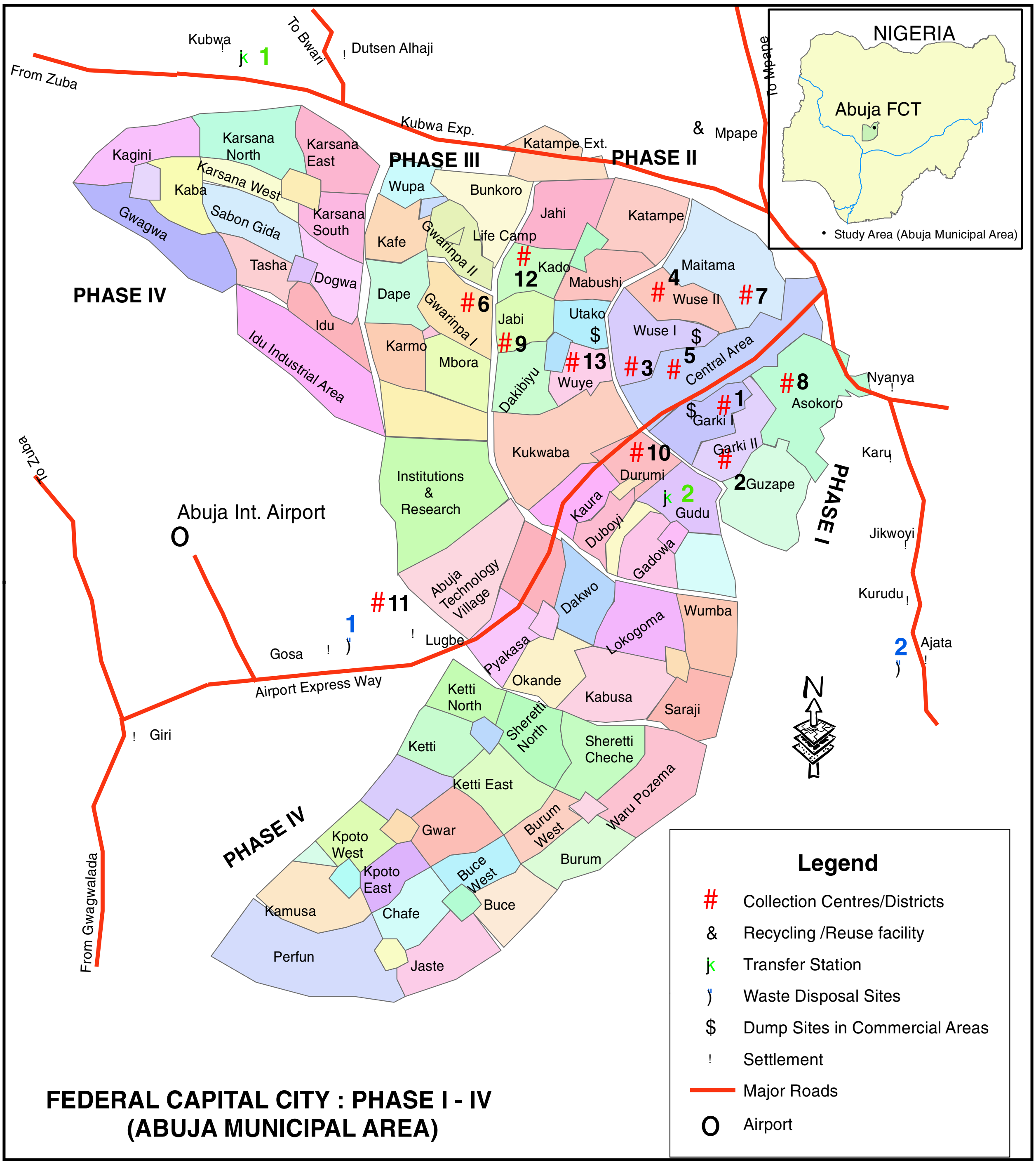
5.1. Percentage levels of recovery and amount of waste moved to disposal sites with benefits from recovered waste materials

The model was considered and solved for various percentage levels of recoveries of reused/ recycled recovered waste materials in the waste management facilities for the daily budgetary provision of AEPB ($12,097.16). Table 8 summarizes the solutions from the solver. It includes amounts of waste evacuated and disposed at the collection centers, amounts required to evacuate the waste left unused after waste evacuation, amounts of waste moved to the disposal sites, and amounts of recycled/reused waste materials recovered.

For example, row 1 of Table 8 shows that when the percentage level of recovery of recovered waste materials in the various wastes management facilities is zero (0.00%), it can be seen that all the wastes were evacuated and disposed of at the collection centers (442.83 tons). The amount required to evacuate the wastes is 9,169.41 USD, amount of money left unused was 2,301.77 USD. The volume of wastes moved to the disposal sites was 442.83 tons. Therefore, no recoveries of waste materials were made (0.00 ton).

When the percentage recovery level was increased to 10% (raw 2, Table 8), it can be seen that the volume of wastes evacuated at the collection centers was 415.91 tons. The money required to vacate the wastes was reduced to 7,784.67 USD (some

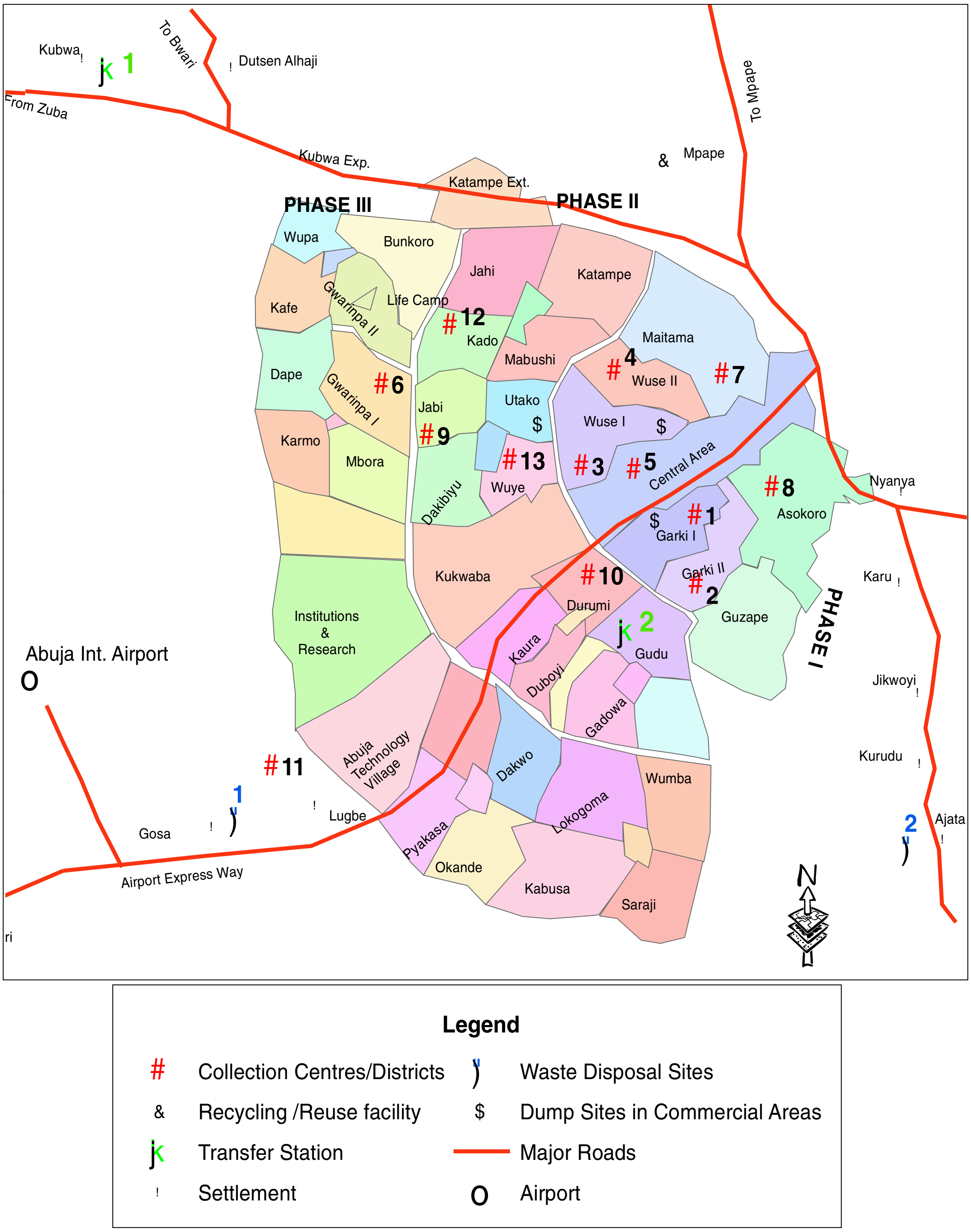
Figure 2
Abuja municipal area (Federal Capital City of Nigeria)



waste materials recovered). The money left unused increased to 4,574.21 USD (due to benefits from recovered waste materials). The volume of wastes moved to the disposal sites was reduced to 378.95 tons (due to recovery of some waste materials made). The amount of recovered recycled/reused waste material was 63.88 tons. Similarly, the solutions to the other percentage levels of waste recovery with the same daily budgetary amount of 12,097.16 USD from AEPB are shown in Table 8.

Figure 4 shows the relationship between percentage levels of recovery of recycled/reused recovered waste materials at waste management facilities and the amount of money required to evacuate and dispose of the waste. The amount of money required to evacuate and dispose of the waste had its maximum value when the percentage level of recovery is zero (0.00%). This is obvious since all the wastes generated were disposed off with no waste materials recovered. At this point, waste management costs

Figure 3
Location of the various wastes management facilities in abuja municipal area



continue to decrease as the percentage levels of recovery of waste materials increase. It was observed that the cost of waste management was at its minimum when the percentage recovery of the waste materials was at 73% (73%); at this point, the cost of waste evacuation and disposal was entirely offset by the benefits from recycled/reused waste materials recovered from the wastes. After this point, the net benefit from recovered waste materials started to accrue gradually and reached its maximum at 100% recovery level. From the above analysis, it is clear that the percentage level of recovery of recovered wastes materials in the various waste management facilities reduces the volume of wastes moved to various waste management facilities and disposal sites

Figure 4
Percentage of recovery level and amount of money required for waste evacuation and disposal

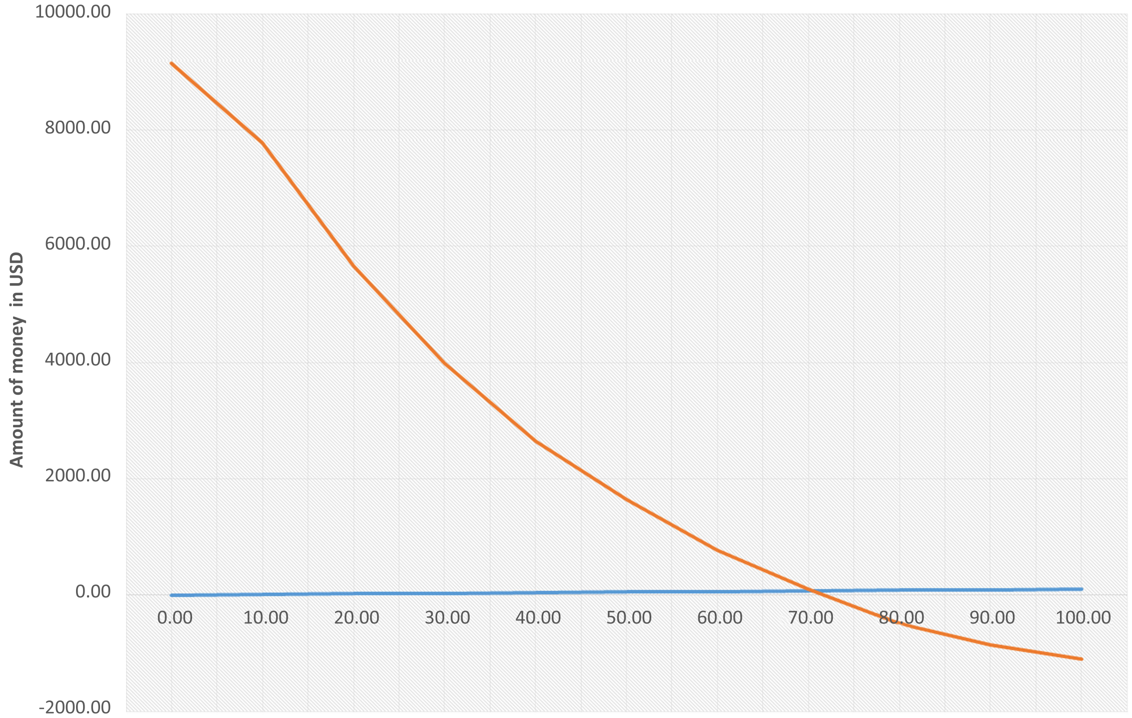


Table 3
Waste evacuation achieved in the collection centres with various budgeted provision

S/No.	Budgetary provision ($)	Fixed cost involve ($)	Amount involve in wastes evacuation ($)	Wastes evacuation in the waste collection centers												
				1	2	3	4	5	6	7	8	9	10	11	12	13
1	625.97	625.97	0.00	26.93	0.00	54.23	17.97	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	1215.01	625.97	589.04	26.93	0.00	54.23	58.83	0.00	0.00	0.00	0.00	0.00	0.00	2.76	0.00	0.00
3	2430.02	625.97	1804.04	26.93	46.59	54.23	58.83	5.40	0.00	0.00	39.44	0.00	0.00	8.55	0.00	0.00
4	3645.02	625.97	3019.05	26.93	46.59	54.23	58.83	27.86	25.51	33.05	47.71	0.00	0.00	8.55	0.00	0.00
5	4860.03	625.97	4234.06	26.93	46.59	54.23	58.83	27.86	26.06	33.05	47.71	37.23	17.60	8.55	9.32	6.27
6	6075.04	625.97	5449.07	26.93	46.59	54.23	58.83	27.86	26.06	33.05	47.71	37.23	17.60	8.55	9.32	6.27
7	7290.05	625.97	6664.07	26.93	46.59	54.23	58.83	27.86	26.06	33.05	47.71	37.23	17.60	8.55	9.32	6.27
8	8505.05	625.97	7879.08	26.93	46.59	54.23	58.83	27.86	26.06	33.05	47.71	37.23	17.60	8.55	9.32	6.27
9	9720.06	625.97	9094.09	26.93	46.59	54.23	58.83	27.86	26.06	33.05	47.71	37.23	17.60	8.55	9.32	6.27
10	10935.07	625.97	10309.10	26.93	46.59	54.23	58.83	27.86	26.06	33.05	47.71	37.23	17.60	8.55	9.32	6.27
11	**12097.16**	**625.97**	**11471.18**	**26.93**	**46.59**	**54.23**	**58.83**	**27.86**	**26.06**	**33.05**	**47.71**	**37.23**	**17.60**	**8.55**	**9.32**	**6.27**
12	12150.08	625.97	11524.11	26.93	46.59	54.23	58.83	27.86	26.06	33.05	47.71	37.23	17.60	8.55	9.32	6.27
13	13365.09	625.97	12739.11	26.93	46.59	54.23	58.83	27.86	26.06	33.05	47.71	37.23	17.60	8.55	9.32	6.27

Table 4
Amount of waste at disposal sites, amount of waste materials recovered and value of *z*

S/No.	Budgetary provision ($)	Total amount of waste removed (in tons)	Amount of waste not removed (in tons)	Amount of waste moved to disposal sites (in tons)	Amount of recycled/reused waste material recovered (in tons)	Amount used to evacuate the waste ($)	Amount left unused ($)	Value of objective function- Z (weighted sum of deviation)
1	625.97	99.13	301.10	88.63	53.11	1409.66	0.00	22.67
2	1215.01	142.75	257.48	127.63	57.73	1998.70	0.00	17.85
3	2430.02	239.97	160.26	214.98	67.60	3213.71	0.00	10.23
4	3645.02	329.26	70.97	294.73	77.14	4428.72	0.00	3.94
5	4860.03	400.22	0.00	359.64	83.19	5643.72	0.00	0.00
6	6075.04	400.22	0.00	359.64	83.19	5791.21	1067.52	0.00
7	7290.05	400.22	0.00	359.64	83.19	5791.21	2282.53	0.00
8	8505.05	400.22	0.00	359.64	83.19	5791.21	3497.54	0.00
9	9720.06	400.22	0.00	359.64	83.19	5791.21	4712.54	0.00
10	10935.07	400.22	0.00	359.64	83.19	5791.21	5927.55	0.00
11	**12097.16**	**400.22**	**0.00**	**359.64**	**83.19**	**5791.21**	**6496.71**	**0.00**
12	12150.08	400.22	0.00	359.64	83.19	5791.21	7142.56	0.00
13	13365.09	400.22	0.00	359.64	83.19	5791.21	8357.57	0.00

Table 5
Model solution with fixed cost (625.97 USD) for waste evacuation and disposal

S/No.	Variable	Original Value	Final Value	S/No.	Variable	Original Value	Final Value	S/No.	Variable	Original Value	Final Value
1	x_{11}	0.00	0.00	31	y_{51}	0.00	0.00	61	w_{92}	0.00	0.00
2	x_{21}	0.00	0.00	32	y_{61}	0.00	0.00	62	$w_{10,2}$	0.00	0.00
3	x_{31}	0.00	49.57	33	y_{71}	0.00	0.00	63	$w_{11,2}$	0.00	0.00
4	x_{41}	0.00	0.00	34	y_{81}	0.00	0.00	64	$w_{12,2}$	0.00	0.00
5	x_{51}	0.00	0.00	35	y_{91}	0.00	0.00	65	$w_{13,2}$	0.00	0.00
6	x_{61}	0.00	0.00	36	$y_{10,1}$	0.00	0.00	66	w_{11}	0.00	31.78
7	x_{71}	0.00	0.00	37	$y_{11,1}$	0.00	0.00	67	w_{21}	0.00	0.00
8	x_{81}	0.00	0.00	38	$y_{12,1}$	0.00	0.00	68	k_{11}	0.00	0.00
9	x_{91}	0.00	0.00	39	$y_{13,1}$	0.00	0.00	69	k_{21}	0.00	0.00
10	$x_{10,1}$	0.00	0.00	40	w_{11}	0.00	0.00	70	k_{12}	0.00	13.62
11	$x_{11,1}$	0.00	0.00	41	w_{21}	0.00	0.00	71	k_{22}	0.00	0.00
12	$x_{12,1}$	0.00	0.00	42	w_{31}	0.00	4.66	72	v_{11}	0.00	55.19
13	$x_{13,1}$	0.00	0.00	43	w_{41}	0.00	15.17	73	v_{12}	0.00	0.00
14	x_{12}	0.00	0.00	44	w_{51}	0.00	0.00	74	s_1^{1-}	0.00	0.00
15	x_{22}	0.00	0.00	45	w_{61}	0.00	0.00	75	s_1^{2-}	0.00	46.59
16	x_{32}	0.00	0.00	46	w_{71}	0.00	0.00	76	s_1^{3-}	0.00	0.00
17	x_{42}	0.00	0.00	47	w_{81}	0.00	0.00	77	s_1^{4-}	0.00	40.85
18	x_{52}	0.00	0.00	48	w_{91}	0.00	0.00	78	s_1^{5-}	0.00	27.86
19	x_{62}	0.00	0.00	49	$w_{10,1}$	0.00	0.00	79	s_1^{6-}	0.00	26.06
20	x_{72}	0.00	0.00	50	$w_{11,1}$	0.00	0.00	80	s_1^{7-}	0.00	33.05
21	x_{82}	0.00	0.00	51	$w_{12,1}$	0.00	0.00	81	s_1^{8-}	0.00	47.71
22	x_{92}	0.00	0.00	52	$w_{13,1}$	0.00	0.00	82	s_1^{9-}	0.00	37.23
23	$x_{10,2}$	0.00	0.00	53	w_{12}	0.00	0.00	83	s_1^{10-}	0.00	17.60
24	$x_{11,2}$	0.00	0.00	54	w_{22}	0.00	0.00	84	s_1^{11-}	0.00	8.55
25	$x_{12,2}$	0.00	0.00	55	w_{32}	0.00	0.00	85	s_1^{12-}	0.00	9.32
26	$x_{13,2}$	0.00	0.00	56	w_{42}	0.00	0.00	86	s_1^{13-}	0.00	6.27
27	y_{11}	0.00	26.93	57	w_{52}	0.00	0.00				
28	y_{21}	0.00	0.00	58	w_{62}	0.00	0.00				
29	y_{31}	0.00	0.00	59	w_{72}	0.00	0.00				
30	y_{41}	0.00	2.81	60	w_{82}	0.00	0.00				

Table 6
Model solution with budgetary provision (2,430.02USD) for solid waste evacuation and disposal

S/No.	Variable	Original Value	Final Value	S/No.	Variable	Original Value	Final Value	S/No.	Variable	Original Value	Final Value
1	x_{11}	0.00	0.00	31	y_{51}	0.00	5.40	61	w_{92}	0.00	0.00
2	x_{21}	0.00	0.00	32	y_{61}	0.00	0.00	62	$w_{10,2}$	0.00	0.00
3	x_{31}	0.00	54.23	33	y_{71}	0.00	0.00	63	$w_{11,2}$	0.00	0.00
4	x_{41}	0.00	19.17	34	y_{81}	0.00	0.00	64	$w_{12,2}$	0.00	0.00
5	x_{51}	0.00	0.00	35	y_{91}	0.00	0.00	65	$w_{13,2}$	0.00	0.00
6	x_{61}	0.00	0.00	36	$y_{10,1}$	0.00	0.00	66	g_{11}	0.00	47.06
7	x_{71}	0.00	0.00	37	$y_{11,1}$	0.00	0.00	67	g_{21}	0.00	30.19
8	x_{81}	0.00	0.00	38	$y_{12,1}$	0.00	0.00	68	k_{11}	0.00	0.00
9	x_{91}	0.00	0.00	39	$y_{13,1}$	0.00	0.00	69	k_{21}	0.00	12.94
10	$x_{10,1}$	0.00	0.00	40	w_{11}	0.00	0.00	70	k_{12}	0.00	20.17
11	$x_{11,1}$	0.00	0.00	41	w_{21}	0.00	0.00	71	k_{22}	0.00	0.00
12	$x_{12,1}$	0.00	0.00	42	w_{31}	0.00	0.00	72	v_{11}	0.00	133.88
13	$x_{13,1}$	0.00	0.00	43	w_{41}	0.00	0.00	73	v_{12}	0.00	0.00
14	x_{12}	0.00	0.00	44	w_{51}	0.00	0.00	74	s_1^{1-}	0.00	0.00
15	x_{22}	0.00	46.59	45	w_{61}	0.00	0.00	75	s_1^{2-}	0.00	0.00
16	x_{32}	0.00	0.00	46	w_{71}	0.00	0.00	76	s_1^{3-}	0.00	0.00
17	x_{42}	0.00	0.00	47	w_{81}	0.00	39.44	77	s_1^{4-}	0.00	0.00
18	x_{52}	0.00	0.00	48	w_{91}	0.00	0.00	78	s_1^{5-}	0.00	22.46
19	x_{62}	0.00	0.00	49	$w_{10,1}$	0.00	0.00	79	s_1^{6-}	0.00	26.06
20	x_{72}	0.00	0.00	50	$w_{11,1}$	0.00	8.55	80	s_1^{7-}	0.00	33.05
21	x_{82}	0.00	0.00	51	$w_{12,1}$	0.00	0.00	81	s_1^{8-}	0.00	8.27
22	x_{92}	0.00	0.00	52	$w_{13,1}$	0.00	0.00	82	s_1^{9-}	0.00	37.23
23	$x_{10,2}$	0.00	0.00	53	w_{12}	0.00	0.00	83	s_1^{10-}	0.00	17.60
24	$x_{11,2}$	0.00	0.00	54	w_{22}	0.00	0.00	84	s_1^{11-}	0.00	0.00
25	$x_{12,2}$	0.00	0.00	55	w_{32}	0.00	0.00	85	s_1^{12-}	0.00	9.32
26	$x_{13,2}$	0.00	0.00	56	w_{42}	0.00	0.00	86	s_1^{13-}	0.00	6.27
27	y_{11}	0.00	26.93	57	w_{52}	0.00	0.00				
28	y_{21}	0.00	0.00	58	w_{62}	0.00	0.00				
29	y_{31}	0.00	0.00	59	w_{72}	0.00	0.00				
30	y_{41}	0.00	39.66	60	w_{82}	0.00	0.00				

Table 7
Model solution with a 12097.16 USD AEPB daily budget for waste evacuation and disposal

S/No.	Variable	Original Value	Final Value	S/ No.	Variable	Original Value	Final Value	S/No.	Variable	Original Value	Final Value
1	x_{11}	0.00	0.00	31	y_{51}	0.00	21.92	61	w_{92}	0.00	0.00
2	x_{21}	0.00	0.00	32	y_{61}	0.00	0.00	62	$w_{10,2}$	0.00	0.00
3	x_{31}	0.00	0.00	33	y_{71}	0.00	33.05	63	$w_{11,2}$	0.00	0.00
4	x_{41}	0.00	0.00	34	y_{81}	0.00	0.00	64	$w_{12,2}$	0.00	0.00
5	x_{51}	0.00	0.00	35	y_{91}	0.00	0.00	65	$w_{13,2}$	0.00	0.00
6	x_{61}	0.00	0.00	36	$y_{10,1}$	0.00	0.00	66	g_{11}	0.00	0.00
7	x_{71}	0.00	0.00	37	$y_{11,1}$	0.00	0.00	67	g_{21}	0.00	129.67
8	x_{81}	0.00	0.00	38	$y_{12,1}$	0.00	0.00	68	k_{11}	0.00	0.00
9	x_{91}	0.00	0.00	39	$y_{13,1}$	0.00	6.27	69	k_{21}	0.00	0.00
10	$x_{10,1}$	0.00	0.00	40	w_{11}	0.00	0.00	70	k_{12}	0.00	0.00
11	$x_{11,1}$	0.00	0.00	41	w_{21}	0.00	0.00	71	k_{22}	0.00	55.57
12	$x_{12,1}$	0.00	0.00	42	w_{31}	0.00	54.23	72	v_{11}	0.00	224.02
13	$x_{13,1}$	0.00	0.00	43	w_{41}	0.00	0.00	73	v_{12}	0.00	0.00
14	x_{12}	0.00	26.93	44	w_{51}	0.00	0.00	74	s_1^{1-}	0.00	0.00
15	x_{22}	0.00	20.77	45	w_{61}	0.00	0.00	75	s_1^{2-}	0.00	0.00
16	x_{32}	0.00	0.00	46	w_{71}	0.00	0.00	76	s_1^{3-}	0.00	0.00
17	x_{42}	0.00	0.00	47	w_{81}	0.00	0.00	77	s_1^{4-}	0.00	0.00
18	x_{52}	0.00	5.95	48	w_{91}	0.00	0.00	78	s_1^{5-}	0.00	0.00

(*Continued*)

Table 7
(*Continued*)

S/No.	Variable	Original Value	Final Value	S/ No.	Variable	Original Value	Final Value	S/No.	Variable	Original Value	Final Value
19	x_{62}	0.00	26.06	49	$w_{10,1}$	0.00	0.00	79	s_1^{6-}	0.00	0.00
20	x_{72}	0.00	0.00	50	$w_{11,1}$	0.00	0.00	80	s_1^{7-}	0.00	0.00
21	x_{82}	0.00	47.71	51	$w_{12,1}$	0.00	0.00	81	s_1^{8-}	0.00	0.00
22	x_{92}	0.00	37.23	52	$w_{13,1}$	0.00	0.00	82	s_1^{9-}	0.00	0.00
23	$x_{10,2}$	0.00	17.60	53	w_{12}	0.00	0.00	83	s_1^{10-}	0.00	0.00
24	$x_{11,2}$	0.00	8.55	54	w_{22}	0.00	25.82	84	s_1^{11-}	0.00	0.00
25	$x_{12,2}$	0.00	9.32	55	w_{32}	0.00	0.00	85	s_1^{12-}	0.00	0.00
26	$x_{13,2}$	0.00	0.00	56	w_{42}	0.00	0.00	86	s_1^{13-}	0.00	0.00
27	y_{11}	0.00	0.00	57	w_{52}	0.00	0.00				
28	y_{21}	0.00	0.00	58	w_{62}	0.00	0.00				
29	y_{31}	0.00	0.00	59	w_{72}	0.00	0.00				
30	y_{41}	0.00	58.83	60	w_{82}	0.00	0.00				

Table 8
Sensitivity analysis to various percentage recovery levels of recovered waste materials

S/No.	Average percentage level of recovery of waste materials	Daily budgetary allocation by AEPB ($)	Amount of wastes in the collection centers (in tons)	Amount of waste evacuated in the collection centers (in tons)	Amount required to evacute the wastes ($)	Amount left unused ($)	Amount of waste moved to disposal sites (in tons)	Amount of recycle/ Reuse recovered (in tons)	Objective function value-z
1	0.00	12097.16	442.83	442.83	9169.41	2301.77	442.83	0.00	0.00
3	10.00	12097.16	442.83	415.91	7784.67	4574.21	378.95	63.88	0.00
2	20.00	12097.16	442.83	386.59	5664.73	7581.85	321.27	121.56	0.00
4	30.00	12097.16	442.83	362.01	3990.73	10143.53	290.27	152.56	0.00
5	40.00	12097.16	442.83	335.09	2652.70	12369.26	248.27	194.56	0.00
6	50.00	12097.16	442.83	308.12	1649.23	14260.43	210.34	232.49	0.00
7	60.00	12097.16	442.83	281.20	780.82	16016.52	176.29	266.54	0.00
8	70.00	12097.16	442.83	254.27	100.40	17584.64	145.89	296.94	0.00
9	80.00	12097.16	442.83	227.35	–485.05	19050.50	118.95	323.88	0.00
10	90.00	12097.16	442.83	200.38	–853.64	20314.07	95.25	347.58	0.00
11	100.00	12097.16	442.83	173.46	–1108.17	21456.29	74.50	368.33	0.00
12	110.00	12097.16	442.83	173.46	–1108.17	21456.29	74.50	368.33	0.00
13	120.00	12097.16	442.83	173.46	–1108.17	21456.29	74.50	368.33	0.00

in the waste management system. This would reduce possible associated problems during waste management in the various facilities, as less volume of wastes were moved to various waste management facilities and disposal sites.

5.2. Managerial insights and practical implications

A multiobjective mathematical programming model (WGP) for solid waste management with comparable importance of collection centers with economic benefits from recovered waste materials was developed. Solid waste management practice, particularly in urban centers of developing countries such as Nigeria, does not consider economic benefits from reuse/recycling recovered waste materials as part of the waste management system. The objectives of the developed models are to:

- minimize the volume of wastes in waste collection centers,
- determine associated minimum cost of waste evacuation and disposal,
- reduce the volume of wastes that can be moved to waste disposal sites, and
- economic benefits from reuse/recycling recovered waste materials were also taken into account based on the percentage level of recovery of reuse/recycle recovered waste material considered.

The model formulated was solved using spreadsheet solver 14.0. The model was solved for various solid waste budgetary provisions. Then AEPB daily budgetary provision of 12,097.16 USD for solid wastes evacuation and disposal in Abuja municipal area is at a 15% recovery level of reuse/recycle recovered waste materials. The model was first solved for the daily fixed cost of the solid waste evacuation (625.97 USD) and then for the total daily budgetary amount of 12,15.01 USD to see the models' responses. For the daily fixed cost of the solid waste evacuation (625.97 USD), the solutions show that all the wastes in collection centers 1 and 2 were evacuated, and 17.97 out of 58.83 tons of wastes were removed from collection center 4. However, no waste was removed in collection centers 2,5,6,7,8,9,10,11,12,13. The level of evacuation recorded here was as a result of benefits from recovered waste materials. Considering the AEPB daily budgetary provision for solid waste evacuation and disposal, the solution shows that all the wastes at the collection centers were evacuated. The total amount of 6,496.71 USD was left unused, which is about 54% of the total daily budgetary provision for solid waste evacuation of the agency.

The average daily solid wastes generation in Abuja municipal is 442.83 tons. With the daily budgetary provision of (12,097.16 USD), and at a 15% average recovery level of reuse/recycling recovered waste materials, the solution shows that 359.64 tons (81.21%) of the total wastes were evacuated and disposed of at a sum of 5,791.21 USD, which is about 48% of the total amount. The waste management facilities include the collection centers, transfer stations, and recycled plants. Recovery of 83.19 tons of reuse/recycle waste materials was made, about 18.79% of the total waste generated. The contribution of about 6% (705.50 USD) of the total amount for the daily waste evacuation and disposal came from recovered waste material at a 15% recovery level.

The various percentage recovery levels for the reuse/recycling recovered waste materials at the waste management facilities were then considered for the same daily budgetary provision to see the responses of the model. At a 0% recovery level, no waste materials were recovered, all the wastes were moved to the disposal sites at the cost of 9,169.41 USD. As the percentage recovery level increases, the amount of money required to evacuate and disposed of the wastes decreases. The minimum amount (0.00 USD) required to evacuate the waste reached at a 71.5% recovery level. At this point, the cost of waste evacuation and disposal was offset by the benefits from waste material recovered (no amount of money or budgetary provision is required for the evacuation and disposal of the waste). Benefits realized from recovered waste materials are enough to evacuate and dispose of the wastes in the collection centers. Any amount realized after 71.5% recovery level is a net benefit from recovered waste materials until when the recovery level is 100%, where maximum net benefit of 1,108.17 USD was realized. The unused amount of money left and the amount of reuse/recycling material recovered continue to increase as the percentage recovery level increases until 100%.

6. Conclusion and Future Work

This study developed the multiobjective mathematical programming model for solid waste management with economic benefits from recovered waste materials and the relative importance of collection centers during waste evacuation. The model minimizes the volume of waste in the various collection centers. It is evident from the solution that less volume of the waste is moved to the disposal sites as the percentage level of recovery of reuse/recycling recovered waste material at the waste management facilities increases. Also, as benefits from recovered waste materials increass, more reuse/recycling recovered waste materials are recovered. With the daily budgetary provision of 12,097.16 USD by the Abuja municipal area solid waste management agency (AEPB), the solution for waste evacuation and disposal shows that, at 0% recovery level, no waste materials were recovered. All wastes at the collection centers were evacuated and disposed of at the disposal sites at 9,169.41 USD.

As the percentage recovery level increases, the volume of waste evacuated and disposed of decreases, the amount of money required to evacuate and dispose of the waste decreases. Also, the amount of money left unused increases. At 71.5% recovery of reuse/recycling recovered waste material, no budgetary provision (0.00 USD) is required to evacuate and dispose of the waste. Benefits realized from recovered waste materials are sufficient to evacuate and dispose of the wastes. After a 71.5% recovery level, the net benefit from recovered waste materials starts to accrue until the percentage level of recovery is 100%. At this point, the net benefit is 1,108.17 USD. The volume of waste shifted to the disposal sites was reduced to 74.5 tons (unrecoverable waste material), which is 16.82% of total waste generated per day, and 368.33 tons (83.18%) of waste materials were recovered.

The study is practical, beneficial financially and can help the Nigerian government tackle solid waste management problems. By extension, it will minimize environmental issues such as GHG emissions, which directly or indirectly harms citizens near to the waste management facilities. Moreover, the recycling of recovered waste materials benefits the governement's revenue generation. This study can be replicable in other developing countries with minor modifications in the model assumptions. In the future, the study has extension potentials to consider the model under different uncertainty scenarios and use robust optimization techniques to solve the problem.

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Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

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