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Community-Based Management of Household Solid Waste for Harare, Zimbabwe: A System Dynamics Approach

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ABSTRACT

Community-based waste management (CBWM) is a waste decentralization approach that carries the potential to divert about two-thirds of household solid waste (HSW) from landfills. Although many studies have suggested this approach to waste management in the city, assessment studies to quantify its material recovery potential are yet to be conducted. This is the gap this study thus aimed to fill. Due to the complex nature of the HSW management system, the study used Network Analysis (NA) findings to inform the development of a system dynamics model. The model was used to assess household-level composting of food leftovers as well as paper and plastic recycling as strategies towards sustainable and integrated HSW management in Harare. A CBWM strategy implementation chart (CBMWSIC) that describes four different strategy implementation levels and their potential benefits for Harare if implemented over a 5-year municipal period (2022-2026) was formulated. According to the author's knowledge, combining NA and SD techniques as done in this study is original work.

Hereafter only referred to as Harare, urban Harare currently realizes an average recycling rate of 5.2% (recycled waste as a percentage of the total HSW generated in the city). However, composting all food leftovers and recycling of 50% paper and plastic in the next municipal period of 2022-2026 is likely to increase it to 34.1%, 41.6%, 51.8%, and 63.1% with each level of strategy implementation. On the other hand, uncollected waste will be reduced by 28%, 55.9%, 55.9% and 62.3%, respectively. Illegally dumped waste is potentially reduced from 224 854tons.yr-1 to 186 009tons.yr-1, 178 496tons.yr-1, 147 440tons.yr-1, and 112 866tons.yr-1, at each implementation level respectively. Controlled waste treatment in the city will also be increased by up to 38.3%. Generally, composting food leftovers is better prioritized in High-Density (HD) and Medium-Density (MD) suburbs, where food waste comprises 33% of the HSW generated. Since HD suburbs carry most of the city population, recycling paper and plastic is also better prioritized here. Overall, Harare can achieve better recycling rates when mixed strategies are applied.

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Introduction

The prevalence of poor municipal solid waste (MSW) management is a primary global concern [1]. While MSW refers to all solid waste produced within a municipality, HSW refers to all waste generated in residential areas. Although mainly consisting of HSW, MSW comprises other waste streams from commercial areas, construction/ demolition sites, and institutions [2,3].

In developing countries, funds to efficiently manage HSW are often insufficient [4,5]. As a result, most municipalities in these countries prioritize waste collection and dumping in landfill sites without prior treatment [6]. Zimbabwe is a developing country in Southern Africa. Poor HSW management is one of the most significant challenges faced [7]. Despite the relevant authority's full acknowledgment of the HSW management issues, the strategies used so far have proven ineffective [5, 8-10].

Harare is the capital city of Zimbabwe. Located in the Northern part of Zimbabwe, the city covers an area of 961km2 and carries a population of 1 851 620 [11,12]. recently published articles extensively describing Harare's HSW management system as well as its challenges [13,14]. Residents in Harare are responsible for sourcing receptacles for HSW storage. There are no transfer stations in Harare. Kerbside collection is the primary method used by the municipality to remove HSW waste from residential areas [14]. The average recycling rate in the city is about 5.2%, with most recycling done at the city's formal dumpsite, Pomona. About 220 waste pickers licensed to work at the dumpsite sell their recovered waste to recycling companies around Harare [15].

Harare's increase in municipal service demand has not supported infrastructure development, mainly due to financial constraints [5,16]. Some of the consequences that poor HSW management has posed for the city include environmental pollution, foul odors, vermin infestation, death, and blockage of sewer systems, among other things [17-19].

Nhubu identified that little to no research has been done so far using Harare as a case study to assess the city's integrated solid waste management options [10]. Due to Harare municipality's financial limitations, recent studies are looking into the potential benefits of community participation in HSW management [20]. There have been reports that Harare has taken up about 3 500 anti-litter monitors within its communities who have proven effective in raising waste management awareness [21]. Moreso, suggested food waste recycling at the household level for urban Zimbabwe to reduce waste collection pressure on the already compromised municipalities [22]. also explored the various decentralization options for Harare to ensure sustainability among which included backyard composting at household level (i.e., composting of HSW) and waste separation at source for material recovery explored in this study [23]. However, did not, but rather suggested that assessment studies to quantify material recovery potential, among other things, be conducted at local level [23]. This is the knowledge gap the study intends to fill. This study thus aims to assess the potential impact of a CBWM system on Harare using system dynamics (SD) modelling techniques. A CBWM system uses separation at source and composting to manage HSW within communities. The system saves landfill space, is low-cost, reduces waste collection pressure, is effective, and increases revenue if the compost generated is sold [6].

Over the decades, several models have been developed to support decision-making tools [24]. As cities continue to grow, models need to be revised to achieve optimal sustainability [25]. SD is a 60-year-old methodology based on feedback control theory used to study complex systems like waste management [26, 27]. This methodology has been widely used in waste management planning [28-30]. STELLA is a user-friendly system dynamic modelling graphical software that helps local governments achieve optimal planning objectives in MSW, hence its preference in this study [31]. For example, the software has been used to develop an SD model for MSW strategy and policy analysis in (Khulna city) Bangladesh, (Tianjin) China, and Pakistan [32-34].

Methodology

The flow of HSW in Harare's current waste management system compared to the proposed CBWM system is illustrated in Figure 1 below. The performance of the HSW management system in Harare is measured using waste management indicators listed in the Service Level Benchmarking (SLB) chart given in Appendix 1. The municipality provided SLB data for the years 2013-2019. The SLB chart uses a set of indicators to assess the annual performance of local authorities. An indicator can act as a descriptive or evaluative function that synthesizes any relevant data to describe complex phenomena or measure the state of a phenomenon over time [1].

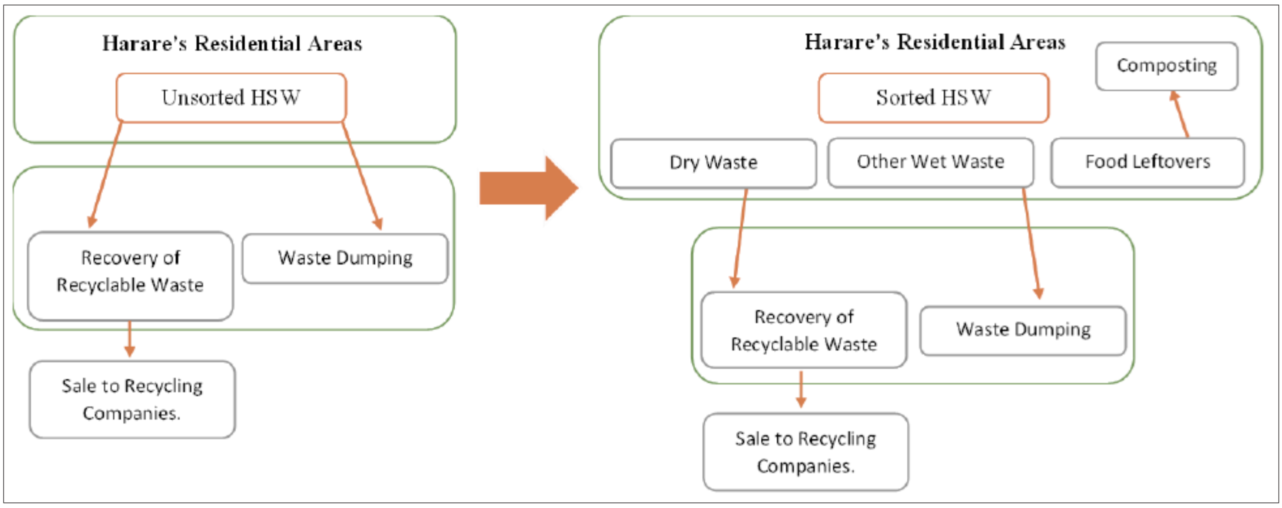

Figure 1: Harare's current versus the proposed HSW stream flow

Model Development and Training

In 1960, Professor J Forrester developed an information feedback methodology called System Dynamics (SD) [35]. This methodology simulates the dynamic nature of various elements within waste management systems. It allows for studying interactions between variables in a complex system over time [36, 37]. It is ideal for policy impact assessment, e.g., in waste generation, waste processing, and waste management options [38]. In this study, a modified process of SD modelling according to Sterman (2000) was adopted as illustrated in Figure 2. In addition to five phases of SD modeling, this study included an initial and additional Network Analysis (NA) phase as shown in Figure 2b.

Apart from the waste management system elements that facilitates waste generation, collection and disposal, there are other aspects that need to be managed to ensure sustainability. For example, financial, institutional, sociocultural, environmental, legal or policy aspects as well as the importance of stakeholder cooperation. The addition of the NA phase to the modeling process was thus designed not only to identify the leverage points within Harare's HSW management system but to also understand the parts of the system that can be simulated given the available data. The NA phase of the modeling process is as presented in Chapter 4 of this thesis. According to the author's knowledge, the combination of NA and SD as done in this study is original.

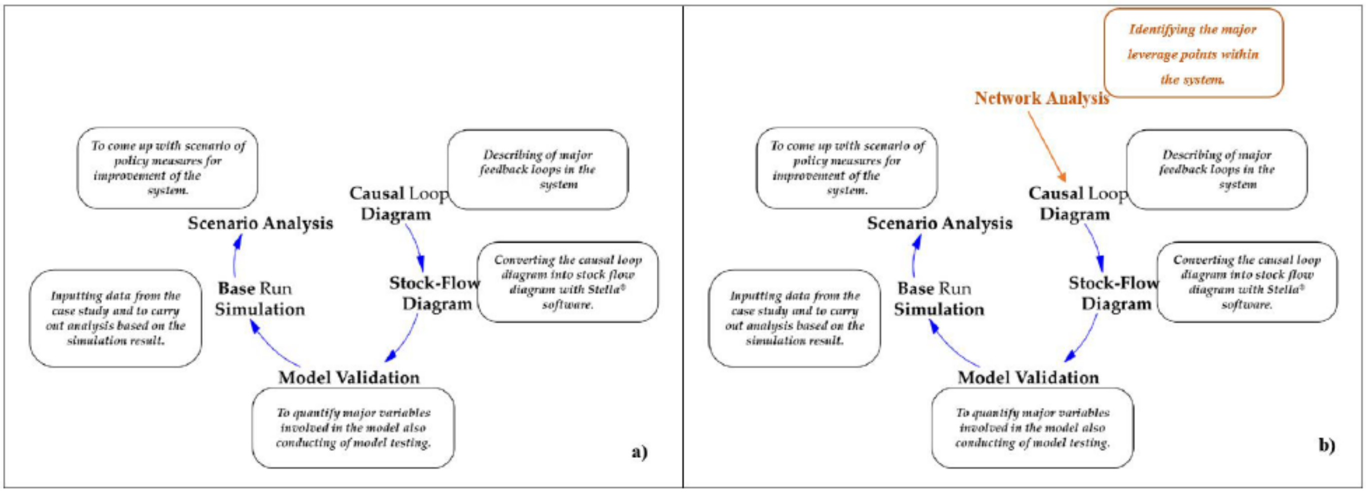

Figure 2: The System Dynamics modeling process a) according to Sterman (2000) as illustrated by Babalola (2019) and b) as modified in this study

Despite findings showing the existence of issues around low stakeholder cooperation, existence of ineffective policies, and negative environmental impact of poor HSW management, the NA study summarized in Chapter 4, revealed that the leverage points within Harare's HSW system are uncollected waste, low waste collection efficiency, illegal waste dumping, bad economy, low financial capacity, low workforce capacity, unreliable waste data, high waste volume, increase in street vendors, no planning and monitoring, no engineered landfills, high waste collection pressure, low waste collection frequency, high unemployment rate, low technical capacity, few waste collection vehicles, low vehicles maintenance, difference in socio-economic classes, high rates of vehicles breakdown, and high population. Applying the 3Rs principle while prioritizing these leverage points suggested that the municipality develop strategies to reduce waste volume, waste collection trips, uncollected waste, amount of workforce, collection pressure, and illegal waste dumping. As a result, and given the municipal data available as summarized in Appendix 1 for the years 2013-2019, focus was placed on simulating particularly the elements (waste generation, collection, disposal and recycling) of the Harare's HSW management system as well as the factors immediately affecting them. Thus, the Causal Loop Diagram (CLD), shown in Figure 3 was built to guide the development of the HSW SD model. The CLD describes the relationships between system elements as well as the relevant performance indicators used to assess solid waste management in Harare.

The Causal Loop Diagram (CLD) was developed using STELLA. The direction and polarity of the arrows show the influence that one variable has on another or rather describe a cause-and-effect relationship between variables. These were determined based on literature studies described in Chapter 3. Various issues affect the HSW management system in Harare. However, the system's leverage points identified in Chapter 4 and the availability of the relevant data were key determinants in selecting the components of the CLD. The arrows in bold show the relationships of variables considered in this study. In contrast, the dotted arrows indicate the existence of some direct links between these variables and others that could not be explored due to the unavailability of data. Identifying and understanding reliable associations between time-series data can be vital in understanding interactions within a system [39].

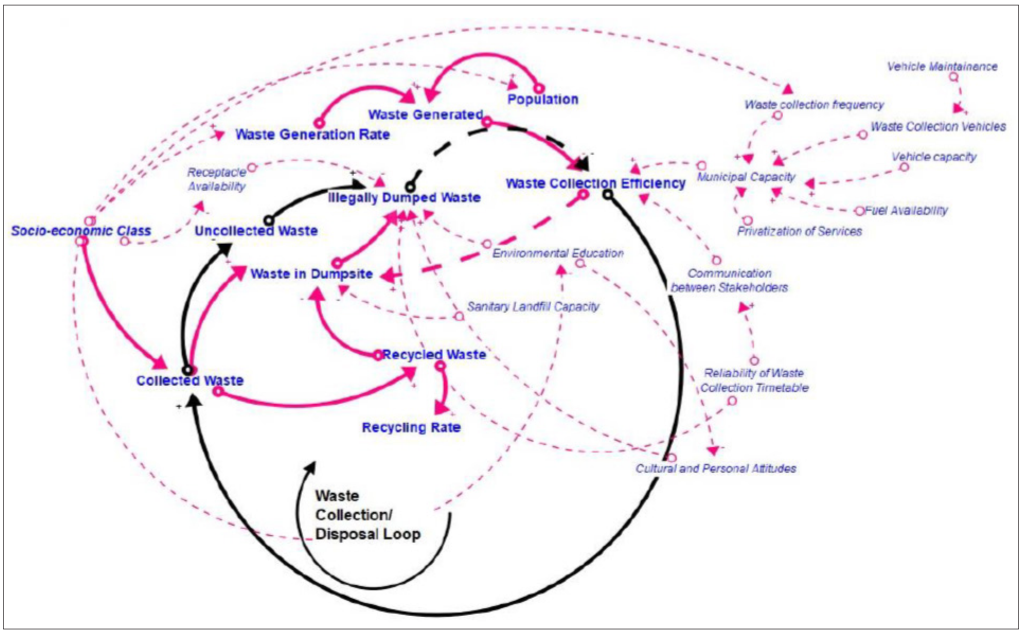

Figure 3: Causal loop diagram used to develop the HSW model

As shown in Figure 3 above, the HSW generated in Harare is directly proportional to population and waste generation rate. The higher the socio-economic class (Low-Density ~10% of the city population, Medium-Density ~30% of the city population, High-Density ~60% of the city population), the higher the population it carries. Waste collection efficiency in Harare depends on the capacity of the municipality to collect the generated waste. In turn, it is determined by factors such as waste collection frequency, the number of waste collection vehicles available, the capacity of the vehicles by weight, the availability of fuel for the waste collection vehicles, and the privatization of part or the entire waste collection service provision. Moreso, issues like poor communication between residents and the municipality concerning waste collection times results in lesser volumes of collected waste. Lower waste collection efficiency thus results in higher amounts of uncollected waste remaining in the suburbs and hence illegal disposal of the waste by residents becomes more prevalent. All collected HSW in Harare ends up in the unsanitary dumpsite, Pomona. As a result, an increase in collected waste means an increase in waste dumped in Pomona hence an increase in the amount of waste illegally dumped. With low waste collection rates, limited environmental education, low reliability of the waste collection timetable, and differences in cultural or personal attitudes, residents resort more to illegal waste dumping before waste collection dates. This contributes to lower waste collection efficiency as there is reduced volumes available for collection per collection area covered. With most recycling done at the Pomona dumpsite, the greater the amount of waste dumped, the higher the waste recycled. Increasing the amount of recycled waste and reducing the amount of waste generated improves recycling rates in Harare.

The Harare municipality provided data used in model development for the years 2013-2019. The HSW model comprises three components: waste generation, collection, and disposal, as shown in Figure 4 below.

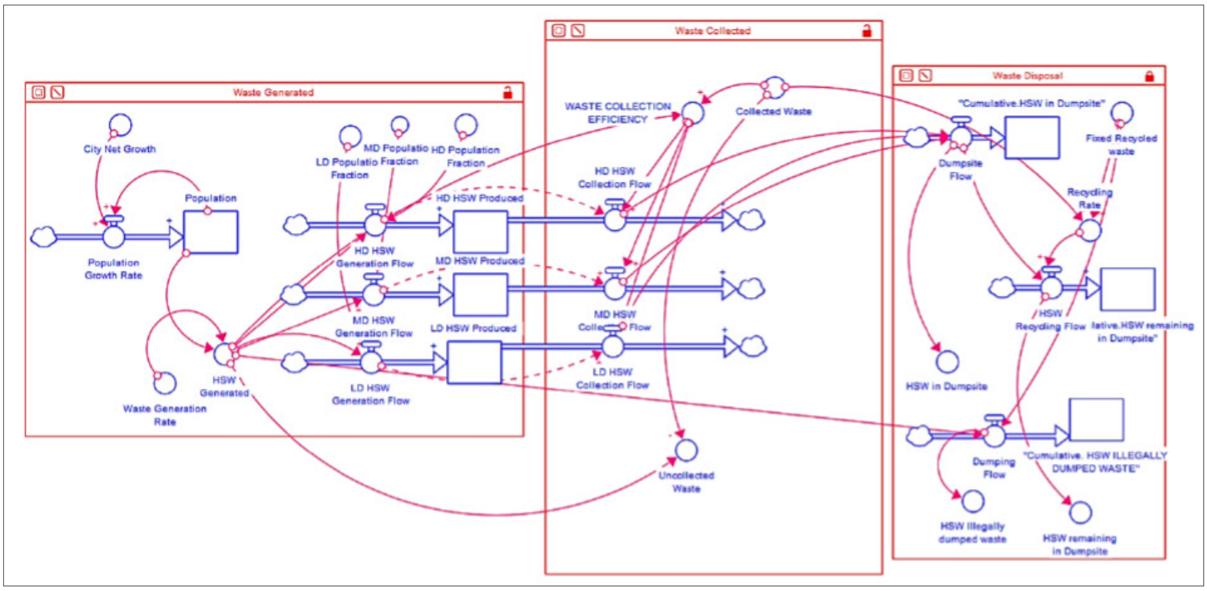

Figure 4: The SD model for HSW management in Harare

Waste Generation Sub-Model

The waste generation sub-model captures waste generation in Harare using the indicators waste generation rate and population. According to the last census report for Zimbabwe in 2012, net population growth and population in Harare is 3.2% and 1 485 231, respectively [40]. Population in the model was calculated using Eq. 2, derived from Eq. 1. An assumption made in this calculation is that the net population growth estimated for Harare in the 2012 census remained the same over the years.

$$\frac{dP_u(t)}{dt} = P_u(t) * P_g \qquad (1)$$

$$P_u(t) = P_i e^{P_g * t} \qquad (2)$$

Where: $\boldsymbol{P_i}$ is the initial Harare population of 1 485 231,
$\boldsymbol{P_g}$ is the population net growth of value 3.2%, and
$\boldsymbol{P_u}$ is the Harare population at a given time *t*.

Waste generated ($\boldsymbol{W_t}$) was calculated using Eq. 3.

$$\boldsymbol{W_t = P_u\, W_g} \qquad (3)$$

Where: $\boldsymbol{W_g}$ is the waste generation rate with a value of 0.1407 tons. capita^{-1}. year^{-1}. This is the average waste generation rate calculated from the municipal data, and $\boldsymbol{P_u}$ is the Harare population at a given time ***t***.

This value also agrees with literature that identifies that $\boldsymbol{W_g}$ in developing countries ranges from 0.073-0.292 tons. capita^{-1}. year^{-1} [41-43].

Waste Collection Sub-Model

When formulating waste management strategies in developing countries, it is critical to consider socioeconomic status [20]. There is no waste generation per capita data for each of the different socioeconomic classes in Harare. As a result, the total waste generated in Harare ($\boldsymbol{W_t}$) was separated into that produced in the different socio-economic classes HD, MD, and LD using Eq. 4.

$$\boldsymbol{W_s = P_f * W_t} \qquad (4)$$

Where: $\boldsymbol{W_s}$ is waste generated in socio-economic class *s*, and $\boldsymbol{P_f}$ is the population fraction of the socio-economic class. It was calculated using Eqn. 5.

Municipal data show that the estimated population fractions for HD, MD, and LD suburbs are 0.6, 0.3, and 0.1, respectively [12].

$$\boldsymbol{P_s = P_f * P_u} \qquad (5)$$

Where: P_s is the population in the socio-economic class, P_f is the population fraction, and P_u is the population at time t.

The waste collection efficiency (E) was calculated using Eq. 6.

$$E = C_t / W_t \quad (6)$$

Where: C_t is the waste collected of 157 486 tons. year^{-1}. This value is the average waste collected value calculated from the municipal data.

Waste Disposal Sub-Model

The waste disposal sub-model captures the primary disposal methods used in Harare, i.e., waste dumping and recycling. The waste management indicators, namely recycling rate and recycled waste, were simulated in this model. All HSW collected by the local authorities ends up in the city's official dumpsite, Pomona, where most recycling happens. Eq. 7 was used to calculate the amount of waste dumped (D) in Pomona.

$$D = \sum_{s=1}^{3} C_s \quad (7)$$

Where: C_s is the amount of waste collected from different socio-economic classes (tons) and C_1, C_2, C_3 represents the amount of waste collected from LD, MD, and HD suburbs, respectively.

To calculate waste recycling rate (R_r) in the model, Eq. 8 was used.

$$R_r = R / W_t \quad (8)$$

Where: R is the amount of recycled waste estimated at 15 434.266 tons.yr^{-1}. This value is the average recycled waste calculated from municipal data available. and W_t is the total waste generated in Harare at time t.

To then calculate the total amount of waste that is illegally dumped in the city (I), Eq. 9 was used. All waste collected from Harare suburbs is disposed of in an un-engineered and unsanitary dumpsite, Pomona. As a result, this waste is counted as illegally dumped waste as well.

$$I = D + U \quad (9)$$

Where: U is the amount of uncollected waste in the city.

Model Testing

Sensitivity Analysis (SA) was used to test the competency of the HSW model. It is a method of uncertainty analysis used to quantitatively assess the effect of varying specific parameters on model output [44]. SA verifies the consistency of model behavior for model calibration or assesses uncertainty [45]. The study used an inbuilt function in STELLA to perform Mathematical SA. While other variables were kept constant, each input variable was varied ±100% of the initial value as shown in Figure 5 below. Changes in the outputs listed in Figure 5 were analyzed each time.

SA Run 1	**Varied Input 1:** City Net Growth	**Test range:** 0-0.064 **Model set value:** 0.032
SA Run 2	**Varied Input 2:** Waste Generation Rate	**Test range:** 0.00001*-0.2847 tons.capita^{-1}.year^{-1} **Model set value:** 0.1407 tons.capita^{-1}.year^{-1}
SA Run 3	**Varied Input 3:** Collected Waste	**Test range:** 0.00001*-314 972 tons **Model set value:** 157 486 tons.year^{-1}
SA Run 4	**Varied Input 4:** Recycled Waste	**Test range:** 0-30868.266 tons. year^{-1} **Model set value:** 15 434.266 tons. year^{-1}

Outputs Assessed
HSW Generated
HSW in Dumpsite
HSW Remaining in Dumpsite
Illegally Dumped Waste

*A non-zero value had to be set to be able to run the analysis

Figure 05: Mathematical SA runs and outputs assessed in STELLA.

The sensitivity parameters were set to follow an incremental distribution, the Sobol sequence sampling option selected and five runs made each time. This was done to visually assess change in model outputs with changes in specific parameters.

SPSS software was used for statistical SA. The study ran linear regression analysis on waste management indicator variables and correlation values (**R** and $\mathbf{R}^2$ values) calculated. As described in Eq. 10, 11, and 12, regression coefficient values were calculated [45-47].

$$S_i = Correlation\,(x_i, y_i) \quad (10)$$

Where: S_I is the sensitivity measure of variable i x_i is the independent variable, and y_i is the dependent variable.

For variables following a linear relationship as described in Eq. 11, the unstandardized regression coefficient (b) was used when all input variables had the same units. When variables had different units, the Standardized Regression Coefficient (SRC) was used as the sensitivity measure calculated in Eq. 12.

$$y_i = a + bx_i \quad (11)$$

$$S_i = b\frac{SD(x_i)}{SD(y_i)} \quad (12)$$

Where: $S(x_i)$ is the standard deviation of x_i, and $SD(y_i)$ is the standard deviation of y_i

Scenario Analysis

In most developing countries, the primary purpose of waste management systems is to increase waste collection coverage and thus reduce illegal waste dumping [1]. This study assesses how introducing a CBWM system (i.e., implementing composting and/ paper and plastic recycling) can potentially impact HSW management in Harare. The study initially ran nine scenarios showing different levels of implementation of the two strategies over the historical period 2015-2019. The level of implementation is measured as the extent of strategy execution in Harare's suburbs, i.e., HD, MD, and LD. Future projections (2022-2026) of the HSW management system used the scenarios yielding the best results at each level of implementation.

Scenario 1: Harare's Current HSW Management System
This scenario represents the baseline. It shows the current state of the HSW management system in Harare. In scenario 1, it is assumed that the system's current state is maintained in the city.

Scenario 2: Scenario 1 + Compulsory Household Level Composting of Food Leftovers

In scenario 2, it is assumed that composting of food leftovers at the household level is introduced in the city. Not only is HD the largest carrier of the population in Harare, but it is also the largest producer of food leftovers, as highlighted in Table 1 below. It is thus essential that composting be a strategy mostly emphasized in these suburbs. Composting of food leftovers in scenario 2 was theoretically assessed as follows:
Implementation Level I: All HD food leftovers (i.e., 53% of the HD HSW produced) is composted.
Implementation Level II: All HD and MD food leftovers (i.e., 53% of the HD HSW produced and 25% of the MD HSW produced) is composted.
Implementation Level III: All HD, MD, and LD food leftovers (i.e., 53% of the HD HSW produced + 25% of the MD HSW produced + 17% of the LD HSW produced) are composted.

Table 1: Household solid waste composition data from nine suburbs in different socio-economic classes [5,7]

	Low Density			Medium Density			High Density		
	S1	S2	S3	S4	S5	S6	S7	S8	S9
% Food leftovers	15	18	17	25	26	23	54	49	55
% Papers	35	32	33	30	31	29	10	14	13
% Wood	9	8	8	10	8	7	9	9	9
% Yard waste	1	2	2.5	7	6	9	2	1	2
% Organic waste	60	60	60.5	72	71	68	75	73	79
% Glass	4	5	4	6	2	4	1	2	3
% Metals	3	4	3	5	2	3	5	4	3
% Electronic	4	5	5	2	2	2	7	6	4
% Plastics	18	16	16.5	22	21	20	9	10	8
% Miscellaneous	11	10	11	3	2	3	3	6	3
% Inorganic waste	40	40	39.5	38	29	32	25	28	21

Besides the economic benefits it provides, composting is an environmentally superior waste management strategy compared to landfilling. Over 200 000 tons of organic waste per year is produced in Harare, most of which is thrown in landfills [48]. Harare shortly ran a composting plant that was not successful due to the high running costs [49]. Introducing household-level composting will potentially encourage the community's involvement in waste management, reduce the amount of waste collection pressure exerted on the municipality, and eliminate direct composting running costs on the city.

Scenario 3: Scenario 1 + Increase in paper and plastic recycling
In scenario 3, it is assumed that the municipality focuses on recycling more paper and plastic HSW. Worldwide, Germany is one of the most accomplished countries in waste recycling achieving municipal waste recycling rates of about 87% [50]. Over the years, paper recycling in the country increased to approximately 82% in 2014 from about 40% in 1990 [50,51]. This study thus assumed a 50% recycling rate for paper and plastic in all scenarios as an initial target for Harare.

As highlighted in Table 1 above, more paper and plastics are generated in LD and MD suburbs than in HD suburbs.

The city can thus prioritize the launch of a recycling strategy in these socio-economic classes as these are likely to yield a more significant change to the HSW management system. The strategy will be assessed in the model as follows:
Implementation Level I: Half of LD and MD paper (i.e., 16.5% of the total LD waste produced and 15% of the MD waste produced) is recycled,
Implementation Level II: Half of LD and MD paper (i.e., 16.5% of the LD waste produced and 15% of the MD waste produced) and plastic (i.e., 8.5% of the LD waste produced and 10.5% of the MD waste produced) is recycled, and
Implementation Level III: Half of all paper and plastic produced in Harare is recycled.

This scenario also assumes that wet and dry waste separation at the source is made mandatory in Harare's suburbs. This way, the municipality collects already separated waste and thus potentially increases waste recovery at the dumpsite. In Implementation Level I, only 50% of paper recycling in the highest producing suburbs was assumed, while in Implementation Level II both paper and plastic recycling was considered. Implementation Level III assesses 50% paper and plastic recycling in all suburbs. Another assumption is that some paper and plastics generated are spoiled, non-recyclable or that residents are noncompliant to waste separation at source. As a result, 50% of the total recyclable waste was deemed reasonable for simulations [7].

Scenario 4: Scenario 2 + Scenario 3
This scenario assumes that each implementation stage of Scenarios 2 and 3 is combined, i.e., food leftover composting and paper and plastic recycling.

Results and Discussions
Results from model testing are as described in Section 4.1. Scenario analysis findings and future HSW management system recommendations are as given in Section 4.2.

Model Testing
Sensitivity Analysis
For all variables in the significant Eq. 3, 6, and 8 used in model calculations, the R values show that the independent variables can explain more than 98% of the total variation in the dependent variables. Moreso, the level of significance expressed as the probability value (p-values) from the ANOVA tests, shows how well the regression equations generated can predict the dependent variables. A p-value of less than 0.05 indicates strong evidence that a relationship exists between variables. For all variables used in Eq. 3, 6, and 9, p-values were less than 0.05. This validates the suitability of their use in simulations.

According to this study, the more influential variables in Harare's HSW management system are HSW collected in Harare ($\boldsymbol{C_t}$), HSW generation rate ($\boldsymbol{Wg}$), and Recycled waste ($\boldsymbol{R}$). This is because a positive regression coefficient value means that the dependent variable increases when the independent variable increases while a negative value signifies vice-versa. When all other variables are held constant, the size of the coefficient value shows the magnitude of change that occurs to the mean of the dependent variable value per unit change of the independent variable. A low percentage error between simulated and actual average data of annual HSW generated (W_t), HSW collection efficiency (E), and recycling rate (R_r) is 1.63%, -4.91%, and 3.60%, respectively was calculated.

Mathematical Sensitivity Analysis

As shown in Table 2 below, while varying city net growth (***P**$_n$*) between 0.016, 0.032, and 0.064, a uniform average HSW in dumpsite (***D***) of 157 486tons.yr-1 was obtained. This is because, during the simulation, all other variables except city net growth are held constant. HSW collected (***C**$_t$*) in the model has a constant value of 157 486tons. $^{-1}$ which was calculated by finding the average HSW collected waste in Harare over the years 2015-2019 using the historical data obtained from the municipality. In Harare, Pomona dumpsite is the official HSW dumpsite, so all collected waste ends up there. If the HSW collected (***C**$_t$*) does not change, the amount of waste that ends up in the dumpsite does not change. This explanation is also applicable for the uniform average HSW remaining in the dumpsite of 142 052tons.yr^{-1} obtained in the simulation. In the model, a constant value of recycled waste of 15 434. 266tons. yr^{-1} is retained. This value is the average amount of recycled waste in the city calculated from historical data.

Table 2: Mathematical sensitivity analysis results for the years

Outputs Assessed	**Original city net growth (*Pn*) = 0.032**	**1X lower city net growth (*Pn*) = 0.016**	**2X greater city net growth (*Pn*) = 0.064**	**Original waste generation rate (W_g) = 0.14235tons**	**1X lower waste generation rate (W_g) = 0.071175 tons**	**2X greater waste generation rate (W_g) = 0.2847 tons**	**Original av. collected waste (C_t) = 157 486 tons**	**1X lower collected waste (C_t) = 78 743 tons**	**2X greater collected waste (C_t) = 314 972 tons**	**Original av. recycled waste (*R*) = 15 434.133 tons**	**1X lower recycled waste (*R*) = 7 717.0665 tons**	**2X greater recycled waste (*R*) = 30 868.266 tons**
Average HSW Generated (W_t) (tons. yr^{-1})	240 288	225 395	273 058	240 288	120 145	480 576	240 288	240 288	240 288	240 288	240 288	240 288
Average HSW in Dumpsite (D) (tons.yr^{-1})	157 486	157 486	157 486	157 486	120 145	157 486	157 486	78 743	240 228	157 486	157 486	157 486
Average HSW remaining in Dumpsite (D_r) (tons. yr^{-1})	142 052	142 052	142 052	142 052	108 370	142 052	142 052	63 309	228 513	142 052	149 769	126 618
Average HSW illegally Dumped (I) (tons. yr^{-1})	224 854	209 961	257 624	224 854	108 370	465 141	224 854	224 854	224 854	224 854	232 571	209 419

Since the HSW collected (***C**$_t$*) and so the HSW in dumpsite (***D***) are the same despite variations in city net growth (***P**$_n$*), the amount of HSW remaining in dumpsite (***D**$_r$*) will be the same since the same Recycled waste (***R***) remains constant.

However, the original city net growth (***P**$_n$*), 1X ***P**$_n$*, and 2X ***P**$_n$* of 0.032, 0.016, and 0.064 yielded an average of the HSW Generated (***W**$_t$*) of 240 288tons.yr^{-1}, 225 395tons.yr^{-1}, and 273 058 tons. yr^{-1}, respectively. The bigger the city net growth (***P**$_n$*), the higher the population (***P**$_t$*) and so the greater the amount of waste generated. Literature supports this finding by identifying that waste generation is proportional to population [5]. This explanation is also true for the HSW illegally dumped (***I***). This is because a non-engineered and non-sanitary dumpsite is the city's primary disposal site. Apart from the recycled waste, whether HSW is collected or not, it is still disposed of illegally. The higher the waste generated, the higher the HSW illegally dumped, as evidenced in Table 2 above.

On the contrary, varying annual waste generation rate per capita (***W**$_g$*) between 0.14235 tons, 0.071175 (1X lower), and 0.14235 (2X higher) yielded HSW in dumpsite (***D***) of 157 486 tons. yr^{-1}, 120 145tons.yr^{-1}, and 157 486tons.yr^{-1} while an output of 142 052tons.yr^{-1}, 108 370tons.yr^{-1}, and 142 052tons.yr^{-1} was generated for HSW remaining in dumpsite (***D**$_r$*). The difference between HSW in dumpsite (***D***) and HSW remaining in dumpsite (***D**$_r$*) can be explained by the fact that ***W**$_t$* < 157 486tons.yr^{-1} which is the HSW collected (***C**$_t$*) constant value set in the model. As a result, less waste was available for collection and disposal to the dumpsite. However, generally for HSW Generated (***W**$_t$*) and HSW illegally dumped (***I***), simulated average values increase as the waste generation rate per capita (***W**$_g$*) increases as also illustrated in Table 2 above.

Even when HSW collected (***C**$_t$*) is varied between 157 486tons.yr^{-1}, 78 743tons.yr^{-1}, and 314 972tons.yr^{-1}, the SA run yields average HSW Generated (***W**$_t$*) and HSW illegally dumped (***I***) values of 240 288tons.yr^{-1} and 224 854tons.yr^{-1}, respectively. This is because, in the simulations, only HSW collected (***C**$_t$*) values are varied while the rest are held constant. The HSW in dumpsite (***D***) and HSW remaining in dumpsite (***D**$_r$*) are higher with higher values of collected waste. However, the latter continues to increase until it reaches a constant value which marks the set value for collected waste, as shown in Table 2 above. This is because, initially, the waste collection capacity of the city is greater than the waste available for collection. As waste production increases annually, it reaches a point where waste collection is higher than the collection capacity, hence the constant value.

When Recycled waste (***R***) is varied between 15 434. 1330tons.yr^{-1}, 7 717. 0665tons.yr^{-1}, and 30 868. 2660tons.yr^{-1}, average HSW Generated (W_t) and HSW in dumpsite (***D***) retain the values of 240 288tons.yr^{-1} and 157 486tons.yr^{-1}, Respectively. However, the HSW remaining in dumpsite (D_r) and HSW illegally dumped (***I***) decrease with an increase in the amount of Recycled waste (***R***) diverted from the dumpsite as shown in Table 2 above.

Scenario Analysis

Results from the preliminary simulations are presented in Section 4.2.1, while the future recommendations for Harare are as shown in Section 4.2.2.

Preliminary Scenario Simulations

Scenario 2 assessed what composting of all food leftovers in each household would have achieved for Harare over the historical 5-year period of 2015-2019. The simulation results show that diverting all food leftovers produced in HD suburbs to composting would have likely increased the recycling rate in the city from 5.2% to 27.0%, as illustrated in Figure 6 below. Introducing composting in MD and LD suburbs would have yielded an increase in the recycling rate by 7.5% and 1.7%, respectively.

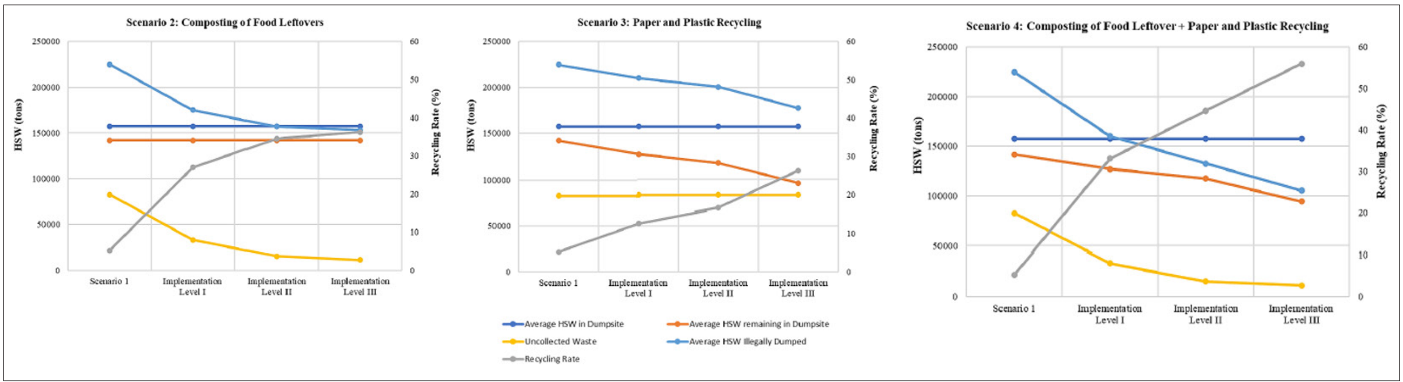

Figure 6: Potential changes in waste management indicator values over the historical period 2013-2019 at different levels of implementation

If waste collection capacity remained at an average of 157 486tons. yr^{-1} over the simulated years, introducing this strategy in Harare would not have changed the amount of waste dumped in Pomona (i.e., all collected waste), and neither would it have changed the average 15 434tons.yr^{-1} HSW recycled at the dumpsite. However, it would have improved the amount of waste treated from 0 to about 71 788tons.yr^{-1}. It would also reduce the amount of HSW left uncollected in communities from 82 802 to 11 014tons.yr^{-1} and the illegally dumped HSW from 224 854 to 153 066tons.yr^{-1}.

In Scenario 3, the study assesses the benefits that paper and plastic recycling would have likely achieved for Harare's HSW management system over the period 2015-2019. Implementation Level III yields the most significant benefits for the city with a 26.2% increase in recycling rate and a 21.1% decrease in the amount of HSW illegally dumped, as illustrated in Fig. 6 above. Although HSW produced in MD and LD suburbs carry higher plastic and paper waste compositions than that generated in HD suburbs, HD suburbs have higher volumes of HSW as they carry about 60% of the city's population. This explains the highest 9.6% increase in recycling rate in Implementation Level III. Although this strategy would not have addressed the issue of the uncollected waste remaining in Harare's suburbs, it would have potentially reduced the amount of waste remaining in Pomona dumpsite by about 32.7%.

The results of Scenario 4 show how combining composting and paper and plastic recycling strategies would have affected Harare's HSW management system over the year range 2015-2019. This combination of strategies would have brought no change in HSW taken to the dumpsite. However, it would have likely increased the recycling rate up to 55.9% from the current 5.2%, as shown in Fig. 5 above. It would also have reduced the amount of waste left uncollected in communities by up to 86.7% and decreased the amount of illegally dumped waste in the city by 53.0%.

Future Recommendations to Improve Harare's HSW Management Systems

This section of the study used the results in Section 4.2.1 to develop a CBWM strategy implementation chart (CBWM-SIC) for the municipal period of 2022-2026. It summarizes the performance of the best scenarios at each level of implementation, as shown in Figure 7 below.

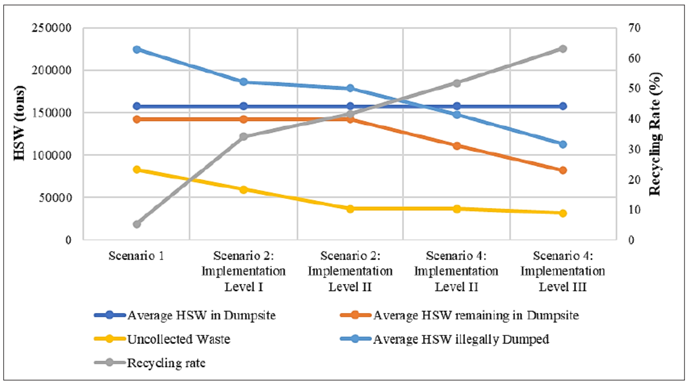

Figure 7: CBWM Strategy implementation chart (CBWM-SIC) for Harare city

Composting (Scenario 2: Implementation Levels I and II) will likely dramatically impacts the HSW management system. It will potentially increase the recycling rate in Harare to 34.1% and 41.6%, respectively. It will probably also reduce uncollected waste by up to 28.0% and 55.9%, respectively. On the other hand, combining composting with paper and plastic recycling (Scenario

4: Implementation Level II and III) will likely increase recycling rates in the city to 51.8% and 63.1%, respectively. Uncollected waste potentially reduces by 55.9% and 62.3%, respectively. The amount of illegally dumped waste can reduce from 224 854tons.yr^{-1} to 186 009, 178 496, 147 440, and 112 866tons.yr^{-1}, respectively.

Conclusions

Reducing the per capita waste generated and increasing the amount of waste recycled or treated in Harare can help reduce the amount of waste in Pomona dumpsite. To reduce the amount of illegally dumped waste in Harare, increasing the amount of waste collected will not be effective since all collected HSW waste ends up in an unsanitary and non-engineered dumpsite. However, a potentially effective strategy can be to increase the amount of waste diverted from the dumpsite through recycling.

This study developed scenarios on how composting HSW food leftovers and recycling 50% of HSW paper and plastic can potentially impact the HSW management system. Material recovery potential assessment studies of waste management approaches like CBWM in Harare is the gap in knowledge this study aimed to fill. Running the scenarios on historical data for 2015-2019 showed that composting food leftovers in Harare's HD, MD, and LD suburbs would have potentially resulted in a 21.8%, 7.5%, and 1.7% increase in recycling rate. A decrease in illegally dumped waste of 22.1%, 10.3%, and 2.6%, respectively, would have been realized. HD suburbs are the highest producers of food leftovers and would have likely realized the most significant increase in recycled waste. On the other hand, implementing 50% recycling of paper and plastic waste alone would possibly have achieved up to 7.4%, 4.0%, and 9.6% increase in recycling rate as well as a 6.6%, 4.6%, and 11.5% decrease in illegally dumped waste, respectively. Adopting Scenario 4: Implementation Level III, which harnesses both composting as well as paper and plastic recycling in HD, MD, and LD suburbs, would have yielded the most significant positive impact on Harare's HSW management system by increasing the recycling rate by 27.9%, 11.5%, and 11.3% as well as reduce illegally dumped waste by 28.7%, 17.2%, and 20.45%, respectively. Should the city of Harare adopt this latter scenario in the next five-year period from 2022-2026, the recycling rate is likely to increase to 63.1%, while illegally dumped waste reduced by about 49.8%, respectively. However, implementing the complete strategy can prove difficult for the local government. As a result, the city can gradually upgrade its HSW management system until this scenario is achieved by following the CBWM Priority Strategy Implementation Chart (CBWM-PSIC) developed and proposed in this study, as shown in Fig. 7 above. The Chart can help the city improve the recycling rate from 5.2% to 34.1%, 41.6%, 51.8%, and 63.1% with each level of strategy implementation. It can also increase controlled waste treatment and reduce uncollected waste by 38.3% and 62.3%, respectively.

Finally, model validation is a continuous process. Future recommendations for this study include obtaining expert and stakeholder input for model improvement and the model's simulation of annual variability in waste management indicators improved. A social survey to understand city residents' approval of these community-based waste management strategies before implementation is also crucial. Moreso, in order to generally gather more insight into integrated waste management, future studies can look into other management frameworks like Integrated Water Management, Integrated Coastal Management or Integrated Port Development and Management [52-58].

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Appendix

Appendix 1 Service Level Bench-marking (SLB) indicator set used for waste management assessment in Harare (HCC, 2019)

3.1	**Coverage of SWM services through door-to-door collection of waste**	
	Definition: Percentage of occupied properties and establishments that are covered by doorstep collection system at least once a week.	
3.1.1	a. Total number of occupied properties and establishments in the service area	The total number of occupied properties and establishments (not properties) in the service area should be established. The service area refers to either the ward or the council boundary
3.1.2	b. Total number of properties with doorstep collection at least once a week	Include doorstep collection by the council itself or council-approved service providers. This includes door-to-door collection systems operated by vendors, etc.
	Coverage = [(b/a) *100]	
	Additional information	
3.1.3	c. Properties with collection daily	
3.1.4	d. Properties with collection once a week	
3.1.5	Properties with collection twice a week	
3.1.6	e. Properties with collection once in more than a week	
3.1.7	f. Total number of properties with some form of collection	
3.1.8	g. Properties with no collection at all	
3.2	**Efficiency of collectio n of municipal solid waste**	

	Definition: The total waste collected by the council and authorized service providers versus the total waste generated within the council area, excluding recycling or processing at the generation point. (Typically, some amount of waste generated is either recycled or reused by the citizens themselves. This quantity is excluded from the total quantity generated, as reliable estimates will not be available for these.)	
3.2.1	a. Total waste that is generated and which needs to be collected	
3.2.2	b. Total quantum of waste that is collected by the council or authorized service providers	The total waste collected from households, establishments, and common collection points. This should be based on actual weighing of the collected waste. Daily generation should be aggregated to calculate the total monthly quantum. This should exclude any special drives for waste collection, and waste generated from one-off activities such as demolitions, desilting canals, etc.
	Collection efficiency = [(b/a)*100]	
	Additional information	
3.2.3	a. Waste generation per capita for the city or town	
3.2.4	b. Weight of loads collected from domestic areas	
3.2.5	c. Weight of loads collected from industrial areas	
3.2.6	d. Weight of loads collected from commercial areas	
3.2.7	e. Weight of loads collected from institutional areas	
3.2.8	f. Weight of loads collected from other areas	
3.2.9	g. Total weight of loads collected by the council	Total figure should be same as figure given in 3.2.2 so checking figure should be zero
3.3	**Extent of recovery of m unicipal solid waste collected**	
	Definition: This is an indication of the quantum of waste collected, which is either recycled or processed. This is expressed in terms of percentage of waste collected.	
3.3.1	a. Amount of waste that is processed or recycled	
3.3.2	b. Total quantum of waste that is collected by the council or authorized service providers	The total waste collected from households, establishments and common collection points. This should be based on actual weighing of the collected waste. This should exclude any special drives for waste collection, and waste generated from one-off activities such as demolitions, desilting canals, etc. (This corresponds to the quantity of (b), as measured for the indicator on collection efficiency). Should be same as 3.2.2
	Extent of recovery of municipal solid waste collected = [(a/b) *100	
3.4	**Extent of scientific disp osal of waste at landfill sites**	
	Definition: The amount of waste that is disposed in landfills that have been designe d, built, operated and maintained as per standards laid down by EMA/SAZ. This extent of compliance should be expressed as a percentage of the total quantum of waste dispose d at landfills sites, including open dump sites.	
3.4.1	a. Total waste disposed in 'compliant' landfills every month.	
3.4.2	b. Total waste disposed in all landfills and dumpsites every month	The total waste disposed after collection and recovery (if any) at landfills (including compliant landfills, open dumpsites and undesignated sites). This quantity should be based on actual measurement at weighbridges preferably located at the entrance to such sites. The monthly total should be the sum of daily totals in a month. Should be same as 3.2.2
	Extent of scientific disposal of waste at landfill sites = [a/b] *100	

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