

Modeling Solid Waste Minimization Performance at Source in Dar es Salaam City, Tanzania

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Abstract

Municipal solid waste generation is strongly linked to rising human population and expanding urban areas, with significant implications on urban metabolism as well as space and place values redefinition. Effective management performance of municipal solid waste management underscores the interdisciplinary strategies. Such knowledge and skills are paramount to uncover the sources of waste generation as well as means of waste storage, collection, recycling, transportation, handling/treatment, disposal, and monitoring. This study was conducted in Dar es Salaam city. Driven by the curiosity model of the solid waste minimization performance at source, study data was collected using focus group discussion techniques to ward-level local government officers, which was triangulated with literature and documentary review. The main themes of the FGD were situational factors (SFA) and local government by-laws (LGBY). In the FGD session, sub-themes of SFA tricked to understand how MSW minimization is related to the presence and effect of services such as land use planning, availability of landfills, solid waste transfer stations, material recovery facilities, incinerators, solid waste collection bins, solid waste trucks, solid waste management budget and solid waste collection agents. Similarly, FGD on LGBY was extended by sub-themes such as contents of the by-law, community awareness of the by-law, and by-law enforcement mechanisms. While data preparation applied an analytical hierarchy process, data analysis applied an ordinary least square (OLS) regression model for sub-criteria that explain SFA and LGBY; and OLS standard residues as variables into geographically weighted regression with a resolution of 241×241 meter in ArcMap v10.5. Results showed that situational factors and local government by-laws have a strong relationship with the rate of minimizing solid waste dumping in water bodies (local R square = 0.94).

Keywords

Modeling Solid Waste Minimization, Dar es Salaam City, Ordinary Least Square (OLS) Regression Model, Situation Factors, Local Government by Laws

1. Introduction

Globally, water bodies are facing serious pollution challenges (Datta et al., 2022; Singh et al., 2022). Coastline pollution, notably plastic waste is a global problem (Lasaiba, 2024; MacAfee & Löhr, 2024). Management of municipal solid waste is part of the world's environmental megatrend of this digital age (Curea, 2017; Płonka et al., 2022). Unprecedented rapid global population, from about 1 billion in 1800 to 7.9 billion in 2020 (Codur, 2021), is linked to expanding urban centers and resource extraction (Codur, 2021; Salem & Tsurusaki, 2024). The profound impact of such an impervious surface is large quantities of runoff and solid waste that ends up in water bodies (Fadugba et al., 2022; Nanda & Berruti, 2021). The world statistics show an increasing trend of solid waste generation to about 2.24 billion tones in 2020, at a rate of 0.79 kg/capita/day (Chakraborty, 2023). Such a trend is linked to rising urbanites, their unique consumption pattern, and the re-definition of space and place.

Across the globe, solid waste management remains to be challenging (Chakraborty, 2023; Codur, 2021). The need for better municipal solid waste management could be a matter of urgency in cities in the global south (Mahale et al., 2023). In such a locality, particularly, coastal cities like Dar es Salaam, poorly managed MSW adversely impacts aquatic ecosystems. As such, the impact proliferates to human health, the environment, and the economy (Chakraborty, 2023; Codur, 2021; Salem & Tsurusaki, 2024). Furthermore, greenhouse gas (GHG) emissions from poorly managed solid waste exacerbate climate change (Gu et al., 2023; Gupta et al., 2022), thus, more destruction in marine ecosystems (Gómez-Sanabria et al., 2022; Gu et al., 2023; Gupta et al., 2022). In this vein, modeling MSW minimization performance at source appears to be a subject of interest for further research.

Solid-waste management encompasses the collecting, treating, and disposing of solid material that is discarded because it has served its purpose or is no longer useful (Fadugba et al., 2022; Khan et al., 2022). MSW minimization is characterized as the reduction of waste from sources and the reuse of waste through recycling (Mostaghimi & Behnamian, 2023). Solid waste minimization is further considered as mechanisms/processes that involve reducing activities and amount of waste materials to a level as low as reasonably achievable (Ojovan et al., 2019). Technically, in industrial settings, waste minimization at sources is applied from the resource's mobilization phase across operations through decommissioning. Waste minimization as a strategy for solid waste management (SWM) can be

applied at the household level, which in this context is a bit contrary to that of the industrial setting (Hussain et al., 2022).

Inculcation of solid waste minimization at the household level involves understanding the common practices commonly applied in solid waste management, as an entry point. It should be clear that SWM practices are not “about one size fits all”. A study done in Dar es Salaam City in Tanzania provides common SWM practices as factors coined in the philosophy of public participation (Muheirwe et al., 2022, 2023; Muiruri, 2022; Sani & Zimucha, 2022; Schenck et al., 2022). In that spirit of public participation, some factors observed to be significant for solid waste minimization at the household level were land use planning activities, availability of landfills, presence of solid waste transfer stations, material recovery facilities, availability of incinerators, strategically positioned solid waste collection bins, presence of solid waste trucks, solid waste budgetary arrangement, and solid waste collection agents. Nonetheless, the solid waste management discipline recognizes all these practices as situational factors.

In practice, land use planning accounts for house typology, house floor area, and family lifestyle; income matter and household size are indirect factors of typology, floor area, and choice of living style (Baiocchi et al., 2022; Liu et al., 2023). Further consideration depicts household numbers to correlate with solid waste transfer stations, which indirectly commands budgetary allocation hence trucks to be aligned for waste ferrying to the landfills (Lockwood, 2023; Reed & Yurechko, 2020). On the other hand, solid waste collection agents (SWCA) are correlated to society profiles, factors such as the size of the population and structure, level of education, employment (both in/formal) (Farooq et al., 2021; Rath & Swain, 2023). It is very likely to find SWCA in areas dominated by the high-class section of society (Marshall & Farahbakhsh, 2013), in such areas, solid waste transfer stations are strategically placed, as such experience timely waste collection and refuse fee collection.

Practically, it could be wrong to assume that situational factors (SFA) alone can effectively be implemented without other supporting instruments. In the context of this study, local government by-law seems to be a strong supporting instrument for effective SFA performance on minimizing solid waste dumping in water bodies (Batista et al., 2021; Muheirwe et al., 2022; Seah & Addo-Fordwuor, 2021; Struk & Bod'a, 2022). Local governments are responsible for planning/allocation and design/feasible technological sourcing and, as such strongly accountable for overall waste management services (Lukacs de Pereny Martens, 2021; Malinauskaite et al., 2017; Mapunda et al., 2023). Such services include, although are not limited to waste removal, storage, and disposal (Lukacs de Pereny Martens, 2021; Malinauskaite et al., 2017; Mapunda et al., 2023). Understanding the policymakers and decision-making machinery on a wide spectrum of solid waste, in particular, municipal waste management is pivotal for effective legal-policy framework contents. On the other hand, community awareness and enforcement mechanisms are keys to the effective performance of solid waste minimization at source (Moh,

2017).

Dar es Salaam city, as it might be to other emerging cities in the world, is facing a serious challenge in municipal solid waste management (Mapunda et al., 2023). Since it is a low technological society, situation factors and local government by-laws are considered strong drivers that when strategically practiced can improve the performance of solid waste minimization at sources in the city. In this discourse, the key question remains, to what extent can situation factors and local government by-laws minimize solid waste at source (water bodies)? To answer this question, research applying geographical information system (GIS) technology for spatial data analysis is inevitable.

2. Waste Management Theory

Municipal solid waste (MSW) encompasses non-utilized or unwanted solid materials (Mapunda et al., 2023; Salem et al., 2020), commonly referred to as trash, rubbish, junk, garbage, and refuse (Ghosh, 2016; Naveen, 2021; Warunasinghe & Yapa, 2016). Management of such a spectrum of materials generated from various sources can be achieved by underscoring a range of interdisciplinary knowledge and skills, referred to as measures (Mirmotalebi et al., 2024). This forms an initial construct of waste management theory (WMT).

“WMT is provided as an effort towards scientification of waste management, it is a conceptual description of waste management, providing definitions of all waste-related concepts, and suggesting a methodology of waste management” (Pongrácz et al., 2004). The main argument in WMT is founded on the expectation that waste management is to prevent waste from causing harm to human health and the environment. In such theory, the term waste seems to be more determined by how waste is defined in a particular community (Concari et al., 2020; Pongrácz et al., 2004). This means that the proper definition of waste is crucial to constructing a sustainable agenda of waste management. So, this study was designed to understand how waste minimization does happen at source, meaning at the household level. Such understanding could help shape policy formulation for solid waste management in Dar es Salaam City, Tanzania.

3. Materials and Method

3.1. Study Area

This research was conducted in Dar es Salaam city, Tanzania’s maritime, commercial, and international gateway on the western coast of the Indian Ocean in the East Africa region. This most industrialized and urbanized region covers a landmass of 1350 km² out of 1800 km² as total area; sits at latitude 6°37'20.4212"S and longitude 39°8'42.0144"E at about 24 meters above sea level. It is home to about 5.3 million people in five districts of Kigamboni, Temeke, Kinondoni, Ubungo, and Ilala, collectively formed by 90 wards (NBS 2002) (Figure 1). The city receives an average of 172 millimeters of rainfall annually, with a maximum and minimum temperature of 29.5°C and 21.7°C, respectively.

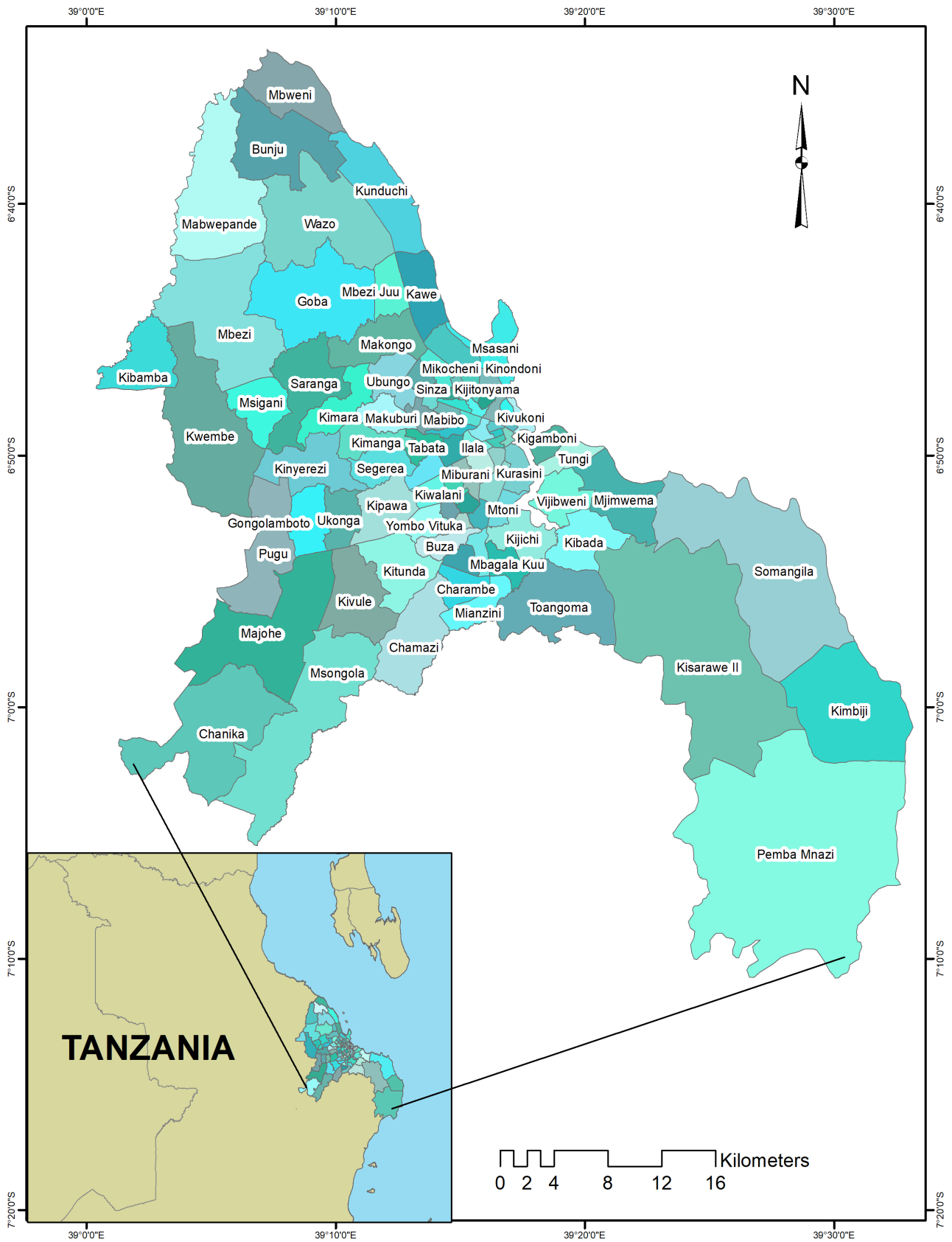


Figure 1. Map of the study area.

3.2. Data Management

3.2.1. Focus Group Discussion (FGD)

The study employed focus group discussion (FGD) for data collection, with respondents being decision-makers at the ward level in the 90 wards of Dar es Salaam city (**Table 1**). The theme of the FGD was to understand how situational factors and local government by-laws can improve the performance of solid waste minimization at sources. Themes and sub-themes are presented in **Table 2**. The study's reference number of wards was 90 based on the Tanzania National Census in 2002. Research data management applied spreadsheet and analytical hierarchy process (AHP).

Table 1. Respondents involved in focus group discussion.

Respondents Designation	No. of Respondents
Ward Executive Officer (WEO)	82
Ward Health Officer (WHO)/Ward Environmental Officer (WEO)	78
Ward Community Development Officer (WCDO)	84
Ward Education Officer (WEDO)	80
Ward Agricultural/Livestock Officer (AGR/LIVO)	64

Table 2. Themes and sub-themes in the focus group discussion.

Themes	Sub-themes
Situational Factors	Land Use Planning: LUP
	Availability of Landfills: AOL
	Solid Waste Transfer Stations: SWTS
	Material Recovery Facilities: MRF
	Incinerators: INC
	Solid Waste Collection Bins: SWCB
	Solid Waste Trucks: SWT
	Solid Waste Management Budget: SWMB
	Solid Waste Collection Agents: SWCA
	Local Government By-Law
Community Awareness: CA	
Enforcement Mechanism: EM	

3.2.2. Analytical Hierarchy Process

The Analytic Hierarchy Process (AHP) is a model developed from mathematical modeling perspectives for management decision-making (Saaty, 2013). The model is part of wide-spectrum multi-criteria decision analysis (MCDA), in MCDA, in most cases, the many qualitative variables in MCDA display conflict patterns. As such, the presence of AHP provides a general measurement model for expressing both qualitative and quantitative factors on a topic of interest. In this research, qualitative/intangible factors need to be converted into quantitative data, thus, facilitating data analysis for spatial mapping. In this case, AHP through a paired-comparison and normalization process, translates qualitative preferences into ratio scaled data. Additionally, the structuring stage of AHP facilitates problem understanding.

In this research, the AHP process for data management is provided in **Table 3**, **Table 4**, **Table 5**, **Table 6**, and **Table 7**. The decision rule is based on consistency ratio (CR), that $CR < 0.1$; this is the validity threshold in the AHP method. CR is a ratio of consistency index (CI) and random index (RI) (Equation (2)). To get CI (Equation (1)), the maximum eigenvalue involves the total sum of the product between each column total in pairwise comparison and the eigenvector (row average weight) in the normalization matrix. The value of RI depends on the matrix order/number of problems (**Table 3**). The final AHP output (Eigenvectors) on each subtheme in **Table 5** and **Table 7** provided useful inputs for further analysis in this study.

$$CI = \frac{(\gamma_{\max} - n)}{(n-1)} \quad (1)$$

$$CR = \frac{CI}{RI} \quad (2)$$

where CI is the consistency index;

γ_{\max} is the maximum eigenvalue;

n is the number of criteria/matrix order;

CR is consistency ratio;

RI is random index.

Table 3. AHP number of criteria.

Number of Criteria/Problems (n)	2	3	4	5	6	7	8	9	10
Random index (RI)	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.51

Table 4. SFA AHP pairwise comparison matrix on DWB.

Pairwise Comparison		LUP	SWTS	SWCA	MRF	SWT	SWMB
Land Use Planning	LUP	1.00	4.00	0.17	3.00	2.00	2.00
Solid Waste Transfer Stations	SWTS	0.25	1.00	0.33	3.00	2.00	2.00

Continued

Solid Waste Collection Agents	SWCA	6.00	3.00	1.00	2.00	2.00	2.00
Material Recovery Facilities	MRF	0.33	0.33	0.50	1.00	2.00	2.00
Solid Waste Trucks	SWT	0.50	0.50	0.50	0.50	1.00	2.00
Solid Waste Management Budget	SWMB	0.50	0.50	0.50	0.50	0.50	1.00
Total		8.58	9.33	3.00	10.00	9.50	11.00

Table 5. SFA AHP normalization matrix on DWB.

Normalization Matrix		LUP	SWTS	SWCA	MRF	SWT	SWMB	Eigenvector
Land Use Planning	LUP	0.1165	0.4286	0.0556	0.3000	0.2105	0.1818	0.2155
Solid Waste Transfer Stations	SWTS	0.0291	0.1071	0.1111	0.3000	0.2105	0.1818	0.1566
Solid Waste Collection Agents	SWCA	0.6990	0.3214	0.3333	0.2000	0.2105	0.1818	0.3244
Material Recovery Facilities	MRF	0.0388	0.0357	0.1667	0.1000	0.2105	0.1818	0.1223
Solid Waste Trucks	SWT	0.0583	0.0536	0.1667	0.0500	0.1053	0.1818	0.1026
Solid Waste Management Budget	SWMB	0.0583	0.0536	0.1667	0.0500	0.0526	0.0909	0.0787

Maximum eigenvalue (γ_{max}) = 6.335; Number of criteria/problems (n) = 6; Consistency index (CI) = (γ_{max})/($n - 1$) = 0.067; Random index (RI) = 1.45; Consistency ratio (CR) = 0.054.

Table 6. LGBY AHP pairwise comparison matrix on DWB.

Pairwise Comparison	COL	CA	EM
Contents of the Law: COL	1.000	2.000	3.000
Community Awareness: CA	0.500	1.000	3.000
Enforcement Mechanism: EM	0.333	0.333	1.000
Total	1.833	3.333	7.000

Table 7. LGBY AHP normalization matrix on DWB.

Normalization Matrix	COL	CA	EM	Eigenvectors
Contents of the Law: COL	0.545455	0.6	0.428571	0.524675
Community Awareness: CA	0.272727	0.3	0.428571	0.333766
Enforcement Mechanism: EM	0.181818	0.1	0.142857	0.141558

Maximum eigenvalue (γ_{max}) = 3.065; Number of criteria/problems (n) = 3; Consistency index (CI) = ($\gamma_{max} - n$)/($n - 1$) = 0.033; Random index (RI) = 0.58; Consistency ratio (CR) = 0.056.

3.2.3. Ordinary Least Square (OLS) Regression

In this study, the main variables of interest were the level of solid waste dumping in water bodies (DWB), situation factors (SFA), and local government by-law (LGBY). From **Table 2**, this study involved main themes (SFA & LGBY), each being explained by several sub-themes. So, the use of ordinary least squares (OLS) (Equation (3)) facilitated the understanding of how a set of variables (sub-themes) can be modeled to explain the main variable (main theme).

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} \cdots + \beta_k X_{ki} + \varepsilon_i \quad (3)$$

where:

Y_i = i^{th} observation of the dependent variable Y , $I = 1, 2, \dots, n$;

X_j = independent variables, $j = 1, 2, \dots, k$;

X_{ji} = i^{th} observation of the j^{th} independent variable;

β_0 = intercept term;

β_j = slope coefficient for each of the independent variables;

ε_i = error term for the i^{th} observation;

n = number of observations;

k = number of independent variables.

3.2.4. Geographically Weighted Regression Analysis (GWR)

Geographically weighted regression (GWR) is a part of the past decade's advent of information technology for data management (Mansour et al., 2021; Ramlan, 2021). GWR as a geographical information system (GIS) built for modeling (Wheeler, 2009) spatial data with a high degree of heterogeneity subscribes to the general regression equation (Equation (3)). In this study, GWR analysis was performed in ArcMap v10.5 using standard residual autocorrelation generated in OLS regression. The GWR analysis presented the results using local R-square.

4. Data Analysis and Results

4.1. Analysis of SFA and LGBY on Minimizing Solid Wastes Dumping in Water Bodies

The understanding of how situational factors (SFA) and local government by-laws (LGBY) minimize solid waste at source applied ordinary least square (OLS) regression. The analysis considered SFA and LGBY to be explained by other factors (**Table 2**), hence the use of the OLS regression model. Using weighted variables (**Table 5** and **Table 7**) in the ArcMap v10.5 platform, the result delivered strong relations between variables in explaining the solid waste dumping minimization in water bodies (**Figure 2**). The Variation Inflation Factor (VIF) (**Table 8**), which is the decision rule in OLS regression was around 1, far below 7.5, the gauge point in OLS spatial analysis modeling.

4.2. SFA and LGBY GWR on Minimizing Solid Wastes Dumping in Water Bodies

Treating SFA and LGBY standard residues from OLS regression as independent

variables and dumping in water bodies (DWB) as dependent variables using Equation (3) in ArcMap v10.5 platform, the regression model delivered **Figure 3**. Generally, SFA and LGBY showed a strong relationship (local R Square = 0.94) in minimizing solid waste dumping in water bodies (DWB).

Table 8. OLS results estimation on variables for solid waste minimization.

Variable	Coefficient	Standard Error	VIF
Situational Factors Influence Solid Waste Minimization at Source			
LUP	-0.077840	0.6319	1.0085
SWTS	0.001462	0.0005	1.5839
SWCA	-0.005548	0.0231	1.5875
Local Government By-Laws Influence on Solid Waste Minimization at Source			
COL	-0.2166	0.5174	1.0014
CA	0.0241	0.0734	1.0014

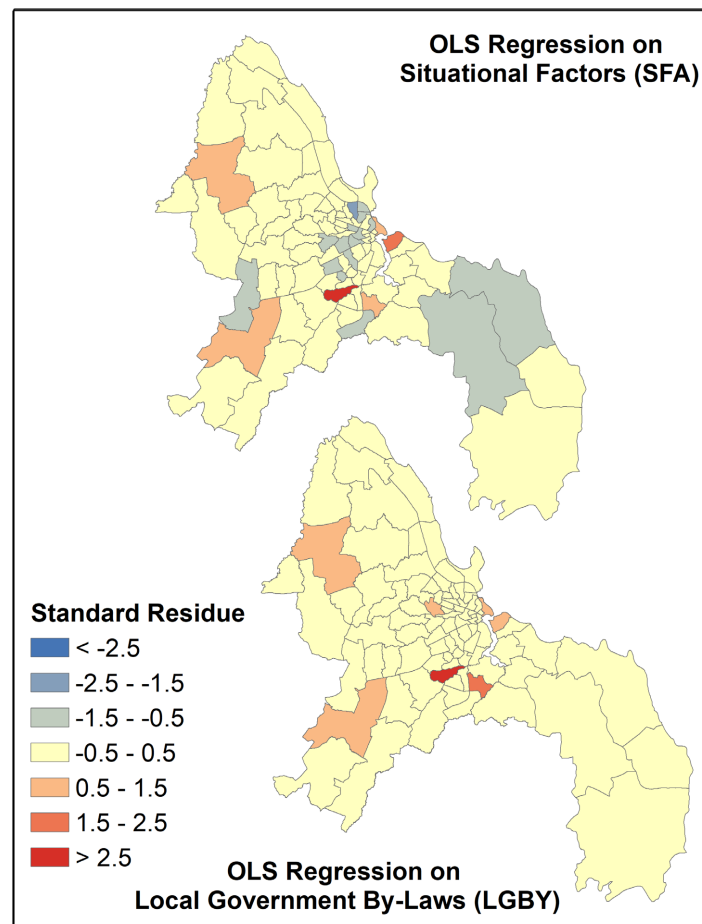


Figure 2. Ordinary least square regression on SFA and LGBY.

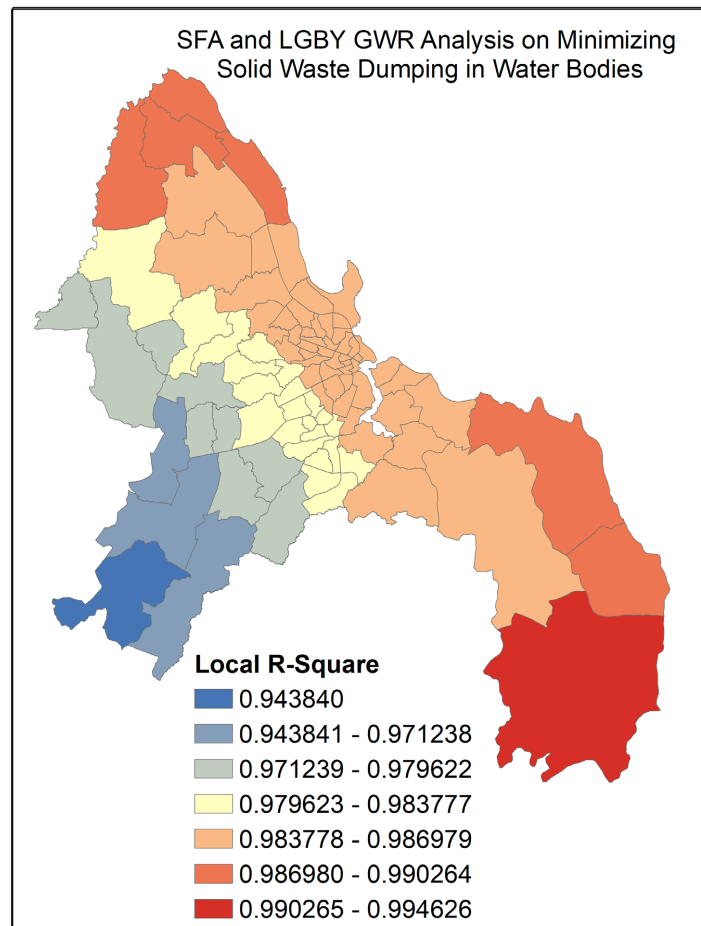


Figure 3. GWR modeling (SFA & LGBY) on minimizing solid wastes dumping in water bodies.

5. Discussion

The findings of this study show situation factors (SFA) and local government by-laws (LGBY) have a great influence on minimizing solid waste dumping in water bodies (DWD). Of the nine sub-criteria that explain SFA, only six (6) showed to be very strong in explaining the role of SFA in minimizing the problem of solid waste dumping in water bodies (**Table 2** and **Table 5**). Analysis shows solid waste collection agents as a pivotal factor in minimizing solid waste at sources (**Table 5**).

Practically, the concept of solid waste minimization involves actions that reduce the amount and toxicity level of waste materials (Pujara et al., 2019; Soni et al., 2022). This study analyzed variables and sub-variables that show spatial analysis of solid wastes dumped in water bodies along the Dar es Salaam coastline. Although collection agents dominate, the study shows that the presence of good land use plans, transfer stations, trucks to ferry the wastes, and an overall budget for solid waste management are profoundly significant for the effective performance of solid waste minimization at sources.

On the other hand, understanding that local government authority is overall in charge of solid waste management brings on board the role of local government

by-laws. From the analysis (**Table 7**) public clarity on the contents of the LGBY outweighs the efforts on community awareness. In the same vein, content and awareness of LGBY to decision-makers is a stronger approach to minimizing solid wastes than generalized enforcement mechanisms at the public level (Nketsiah-Essuon, 2022; Nnamani & San, 2023).

While situational factors are explained in the context of waste transfer, collection centers, storage techniques, ferrying mechanisms, and overall disposal mechanisms, in practice, functional LGBY can guarantee the effective implementation of one or all SFA. LGBY guides local government officers at the ward level among other instruments of enforcement mechanism.

The theoretical perspective on spatial analysis results displayed in **Figure 2**, from OLS regression shows that far negative and far positive standard residues indicate redundancy in explanatory variables (Gao et al., 2022; Hajiloo et al., 2019). Nonetheless, the smaller the standard residue, the stronger the model in explaining the subject of interest (Wu et al., 2019). Thus, from **Figure 2**, modeling situational factors and local government by-laws as drivers of minimizing solid waste dumping in water bodies in Dar es Salaam city seem to be working effectively. Theoretically, the closer the value of R-square to 1, the higher the value of VIF, hence the higher the chances of multicollinearity with the particular independent variable. So, to avoid multicollinearity error, the sub-criteria that explain the SFA and LGBY were modeled in OLS regression. Thereafter, standard residue from OLS was used as input in GWR to model SFA, LGBY, and DWB. In either case, the VIF of less than 1.5 in OLS regression and R-square of 0.9 in GWR analysis are facts that explain the best modeling results on how SFA and LGBY can be applied to reduce solid waste dumping at source (DWB) in Dar es Salaam city.

6. Conclusion

In this article, the study has found that solid waste management performance, in particular minimizing the dumping in water bodies in Dar es Salaam city can be realized by investing in land use planning, solid waste transfer stations, solid waste collection agents, material recovery facilities, solid waste trucks, and solid waste management budget. The aforementioned variables, which explain situational factors in integration with contents and community awareness of the local government by-laws, can deliver an efficient municipal solid waste management framework. Such a policy framework can be tailored to strategies that cutter the needs of the community at the ward administrative level, concerning waste collection, treatment, and disposal hence minimizing performance at sources.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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