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Optimizing Waste Management in Lhokseumawe City: a GIS-Based Needs Assessment for Collection Facilities to Mitigate Illegal Dumping

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***Abstract*—Solid waste management is a significant urban issue in Indonesia. This is exacerbated by rapid population growth and urbanization, which are not accompanied by sound waste management practices, such as a lack of infrastructure and widespread illegal dumping. This paper presents a data-driven methodology for analyzing trash generation patterns and identifying infrastructure requirements using a Geographic Information System (GIS). The goal is to create a data-driven strategy for identifying optimum Waste Collection Locations (WCPs) in order to improve service efficiency and reduce environmental impact. The study results show that Lhokseumawe City produces 530 m³ of waste daily. Therefore, Lhokseumawe City requires 44 strategically located waste disposal sites, taking into account existing illegal dumping locations and population density. An additional 21 garbage trucks are also needed to manage the urban waste generation volume. This indicates a significant shortage of waste management facilities to serve the population. This study presents a practical plan for local governments, including optimal WCP locations and designs, to achieve the SDGs goal of becoming a sustainable city.**

Keywords— solid waste; waste generation; waste collection point

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I. INTRODUCTION

Solid waste is one of the significant problems in Indonesia, with the increasing population, urbanization, changes in consumption patterns, economic growth, and technological advances in society, thus increasing the amount of waste generated. All stakeholders must pay attention to the waste problem because it is a social phenomenon. Waste, which we can call a by-product of human activities, has caused increasingly complex problems.

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An optimal waste transportation system is one indicator of good waste management. Waste transportation moves waste from WCP or waste collection sites to the landfill. The growth rate of solid waste generation greatly influences waste transportation increasing the need for a waste transportation fleet and cost. In waste transportation planning activities, the selection of vehicle routes and transportation schedules determine the total distance of the trip [1].

The operational subsystem of waste management includes the basics of planning, including collecting, processing and final disposal of waste. The activity involved in managing waste from its source to its final disposal is collectively called waste management. Waste management aims to collect waste from the source of waste generation and send it to the landfill [2].

Households are the main producers of solid waste in Indonesia [3], [4]. Indonesia has currently implemented several community-based waste management efforts to reduce the burden of waste transportation and processing [5], [6], [7], [8]. However, the more the problem of uneven waste distribution increases poses a significant challenge, including the lack of limited disposal capacity. A strong positive correlation evidences between population growth, the Gross Domestic Products and the methane generation from solid waste [9]. With the increasing waste generation and environmental risk, the current waste management facilities and infrastructure will certainly not be adequate.

Indonesia's existing waste collection system faces several challenges, including illegal waste distribution across the city [10], inadequate infrastructure to support efficient collection [11], and the potential for increased waste generation due to ongoing population growth. Not only in Indonesia, several other countries are also experiencing this problem, such as in India [12], Italy [13], South Africa [14], and the United States [15].

Lhokseumawe City, as a medium city, urgently needs to implement Geographic Information Systems (GIS) from the immense pressure that rapid urbanization places on outdated waste management systems. Traditional methods are often inefficient and costly, leading to significant environmental risks. GIS provides a critical, data-driven solution by optimizing collection routes to reduce fuel consumption and expenses and scientifically identifying suitable locations for landfills and bins to mitigate public health and environmental impact. Furthermore, it integrates diverse data into a single platform, creating a powerful decision support tool for identifying underserved areas, planning infrastructure needs like additional bins, and enhancing overall service efficiency through better resource allocation and citizen engagement.

Geographical Information System is widely used in land use and land cover research, evaluation of rural built environment and controlling illegal dumping through mapping application [13], [16]–[18]. Currently, there is no research to plan and map the existing waste illegal dumping by data-driven plan for the city's waste collection infrastructure, addressing the inadequacy of existing facilities in the face of growing waste generation. This study was conceived to fill that gap by employing Geographic Information Systems (GIS) techniques to analyze spatial patterns of waste generation, assess the efficiency of existing collection routes, and identify optimal locations for new or relocated WCP facilities [19].

II. METHOD

This research is conducted in direct field observation to sampling illegal dumping waste distribution and to find out existing waste transportation and management conditions in Lhokseumawe city, Aceh, Indonesia. Besides, it was collected data from government environmental service, such as number of waste transport vehicles, total waste generation and waste transportation route.

In waste management planning, it was important to determine the existing waste generation volume predicted by the city population. Using geometric method, Lhokseumawe City population data for 2023 was obtained by projecting population data from 2021 and 2022. Based on SNI 19-3893-1995, Lhokseumawe city with 192,867 population in 2023 classified as medium city, so that waste generation for medium city is 2.5-2.75 L/person/day or 0.7-0.8 kg/person/day.

After estimating the population and waste generation volume, the requirement for waste facilities, including truck fleets, can be estimated. The WCP design and requirements are referred to SNI 19-3964-1994 concerning procedures for selecting locations for final waste disposal sites. Spatial software is used to map waste distribution locations and proposed WCP locations. So that it can determine the need for WCP which can be determined from SNI 19-3964-1994 and the transportation fleet using the following formula:

$$Nt = Vs / Vb \quad (1)$$

Where, Nt is number of waste transportation needs, Vs is total volume of waste (m^3), and Vb is total volume of vehicle capacity (m^3/rit).

III. RESULTS AND DISCUSSION

Lhokseumawe City has four Districts: Blang Mangat District, Muara Satu District, Muara Dua District and Banda Sakti District. The amount of waste in Lhokseumawe City depends on the number of residents, the increasing number of residents the more waste generation. Lhokseumawe City is classified as medium city based on the number of residents. The number of population and predicted waste generation volume as can be seen in Table 1.

Lhokseumawe City's waste in 2023 is 530 m^3/day or 193,590 m^3/year. Banda Sakti District has the highest population and the largest volume of waste generated, 216 m^3/day or 78,822 m^3/year. Along with the increasing population, the waste generation volume will also increase every year. The more waste there is, the more the government must pay attention to the facilities needed, especially in handling waste disposal. For example, increasing the number of waste disposal sites in each area, both in villages and sub-districts, really needs to pay attention to the number of waste transportation fleets needed to transport waste to the landfill.

TABLE 1.
WASTE GENERATION

Subdistrict	Population (Person)	Waste Generation		
		(L/day)	(m^3/day)	(m^3/year)
Blang Mangat	27,432	75,438	75	27,535
Muara Dua	52,693	144,906	145	52,891
Muara Satu	34,214	25,661	26	9,366
Banda Sakti	78,528	215,952	216	78,822
Total	192,867	530,384	530	193,590

Direct interviews were also conducted with the community to find out the problem of waste illegal dumping. After that, the problems were categorized into management, service, and facility problems. Details of the problems can be seen in Table 2. Similar problems are also often experienced by other areas, including the absence of waste sorting in households, lack of community participation, and weak government regulations. High costs are also one of the most important obstacles in waste management, by selecting the shortest route it is hoped that costs can be reduced. In addition, the route can be further shortened by optimizing waste transportation facilities through the WCP availability.

TABLE 2.
WASTE MANAGEMENT PROBLEM

Main Problems	Details Problems
Management	- Lack of waste management funds
	- High operating costs
	- The manual administration of waste management funds
Service	- Inefficiency in the collecting retribution fees process
	- The transportation service cannot reach all the houses in the village on every trip
	- Low community engagement in joining waste transportation services
Facilities	- No temporary waste disposal
	- No sorting facilities
	- Lack of waste vehicle

From the results of population data and waste generation volume, the requirement for waste facilities (WCP and truck fleets) can be estimated. Calculating waste facilities and infrastructure needs is necessary to determine how much WCP and waste transportation fleets (trucks) are needed. More specifically, the amount of waste generated determines the size of waste facilities, including number of wastes collecting transportation, routes number, and WCP size. To be a consideration in deciding the location of the WCP, mapping of waste distribution points is required as depicted in Figure 1.

The provision of waste facilities is an important priority in funding/budgeting in Lhokseumawe City. With the addition of waste facilities to accommodate waste so that the comparison of the amount of waste produced by residents and the facilities to accommodate and transport waste to WCP and from WCP to landifll is balanced.

a. WCP Requirements

WCP requirement analysis aims to determine the size of WCP in Lhokseumawe City based on the volume of waste generated each day. Based on this. Total waste volume data for each sub-district is needed to calculate the number and capacity of WCP by referring to the ideal WCP capacity standards (12 m^3) based on SNI 03-1733-2004. The WCP requirements in Lhokseumawe City can be seen in Table 3.

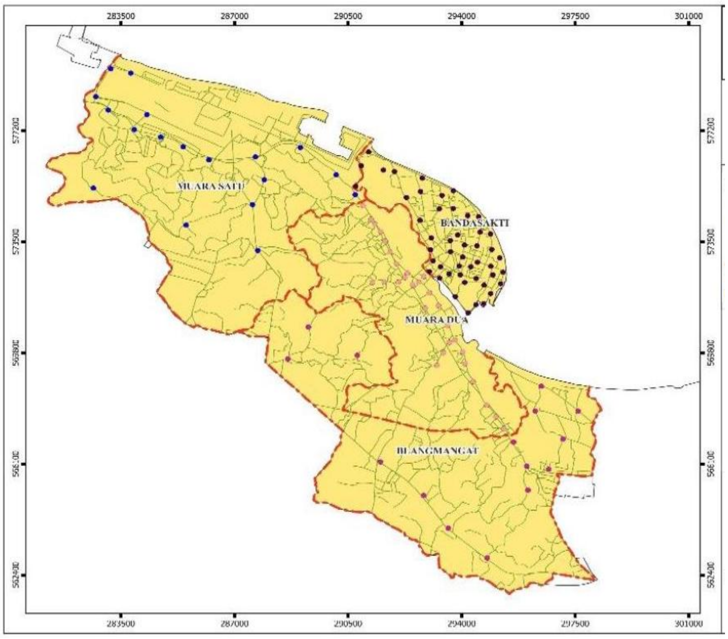

Figure 1. Waste Distribution Patterns Map

TABLE 3.
NUMBERS OF WCP REQUIREMENTS

No.	Subdistrict	Population (People)	Waste Volume		Capacity Standard WCP (m^3)	Number of existing WCP	WCP requirements
			Liter/day	m^3/day			
1	Blang Mangat	27,432	75,438	75		-	6
2	Muara Dua	52,693	144,906	145		-	12
3	Muara satu	34,214	94,089	94	12	-	8
4	Banda sakti	78,528	215,952	216		1	18
	Total	192,867	530,384	530		1	44

\ased on the Table 3, WCP requirements in Lhokseumawe city are 44 units to relocate all city waste generation. However, based on existing data, the number of existing WCP is 1 unit in Banda Sakti District, so the addition of WCP in Lhokseumawe City need 43 additional WCP. The increasing population causes the increasing amount of waste. It is not balanced by an increase in adequate waste infrastructure because the availability of WCP in an area is still minimal, impacting the decline in environmental quality.

Illegal dumping waste represents an economic, environmental, and social risk. Leachate produced from waste can contaminate groundwater and surface water, also emissions and smoke from open burn waste are harmful to humans and the environment.

Analysis of the suitability of WCP land must be known in determining the research location, this is done to see the natural carrying capacity to accommodate urban activities. The capacity of the WCP greatly influences the radius of WCP service. The greater the capacity of the WCP, the further the service. The main requirement in determining the location of this WCP is that it is easily accessible to the public and as close as possible to the source of waste. The provision of waste infrastructure and facilities that the WCP service radius is at least 1 km or 1000 m, while the distance of the road to the residential area, the minimum distance from the WCP to the residential area is 50 m. Map of WCP plan is can be seen in Figure 2.

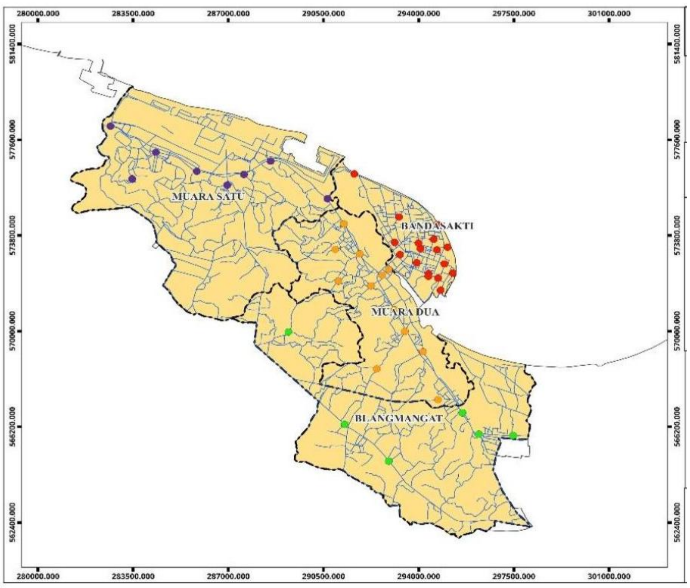

Figure 2. WCPs Plan Map

The existence of WCP is certainly very beneficial for residents and also to minimize the time for transporting waste so that it is easier for waste collection workers so that they do not pick up waste at each waste point. In addition to minimizing transportation time, it can also minimize the distance for transporting waste so that it is faster to transport waste.

The WCP is designed has a volume of 6 m^3 which refers to SNI 03-1733-2004 the need for waste facilities and infrastructure with a length of 330 cm, a width of 180 cm and a height of 120 cm using brick walls. This WCP design planning can make it easier for the government to plan the construction of WCP for each District. WCP detail design can be seen in Figure 3.

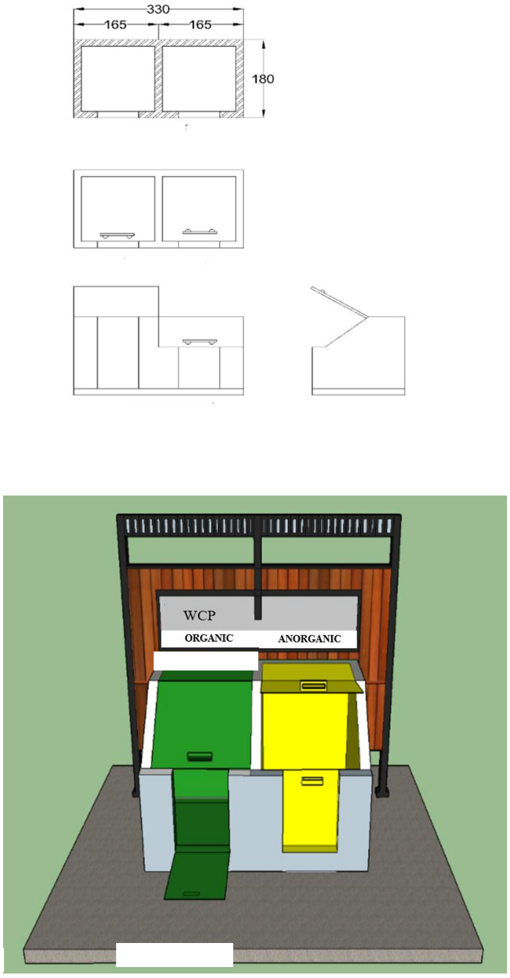

Figure 3. WCPs Design

b. Waste Transportation Fleet Needs

The waste transportation needs of Lhokseumawe City in 2023 with a total waste generation of 530 m^3/day. The Lhokseumawe City waste transportation fleet currently has 23 trucks with a transport capacity of 6 m^3 and from the calculation of the number of trips per day (Nd) in the analysis results of waste transportation activities in Lhokseumawe City, the average transportation trip is 2 trips/day.

An assessment of Lhokseumawe City's 2023 waste transportation requirements indicates a total need for 44 trucks. However, the city's current operational fleet consists of only 23 trucks, creating a significant deficit of 21 units. To address this shortage and ensure adequate service coverage, the strategic plan needs more 21 trucks, each with a proposed capacity of 5 m^3 (Table 4).

TABLE 4.
WASTE TRUCKS REQUIREMENTS ANALYSIS

Waste Generation, Vs (m^3/day)	Waste Trucks Requirements, Nt (unit)	Waste Trucks Number Existing (unit)	Waste Trucks Additional (unit)
530	44	23	21

The results of this study reveal a critical disconnect between the current state of waste management infrastructure in Lhokseumawe and the city's legal mandates and international sustainability commitments. The calculated need additional 43 WCPs and 21 waste trucks showed a significant infrastructure deficit. This condition not only emphasis the illegal dumping location documented in Figure 1 but also fundamentally hinders the successful implementation of Waste Management Regulation. This local regulation aims to improve public health and environmental quality by establishing a structured waste management system. However, without the necessary facilities for collection and transport, the Regulation’s objectives remain aspirational rather than operational. This research, therefore, provides an essential, evidence-based roadmap that aligns with the national push for waste management reform, offering a practical blueprint for the local government to translate policy into action.

The proposed plan directly advances several United Nations Sustainable Development Goals. It addresses SDG 11 (Sustainable Cities) by offering a clear path to manage municipal waste and reduce the city's environmental impact under Target 11.6. By mapping illegal dumps and planning for 44 strategically located

WCPs, this study offers a direct pathway to controlling municipal waste, improving the urban environment, and making the city more sustainable and resilient. In addition, this research also supports SDG 3 (Health) and SDG 6 (Water) by mitigating pollution from illegal dumpsites, including harmful emissions and water-contaminating leachate. Moreover, the proposed WCP design encourages waste sorting at the source, a foundational step for promoting recycling and waste reduction, aligning with the objectives of SDG 12 (Responsible Consumption and Production).

Moreover, this research transcends a simple facility count; it provides a strategic and actionable framework that connects grassroots data to local law and global goals. By addressing the severe lack of infrastructure, Lhokseumawe can not only enforce its waste management regulations but also make significant and measurable progress toward creating a healthier, more sustainable, and resilient urban future in line with the SDGs [20].

The research properly indicates the need for 21 extra waste transportation units to meet the city's requirements. However, merely adding more vehicles is only half of the answer. Braga et al. found that geoprocessing and GPS tracking of collection trucks can be utilized to assess and optimize existing collection routes [21]. A GIS-based system can automatically determine the most efficient collection routes for the whole fleet by mapping elements such as road conditions, traffic congestion patterns, turn limitations, and smart bin fill levels in real time. These ensures that the vehicles are used efficiently, reducing fuel consumption, labor hours, and operational cost. It is important since the city has limited resource-constrained municipal budgets.

Effective environmental management requires a holistic approach that synergistically integrates geospatial analysis from GIS, real-time data acquisition via the Internet of Things (IoT), and a nuanced understanding of local socio-cultural contexts. One of the most effective uses of this approach is to identify "hidden hazards". Neighborhood participants were given a co-designed mobile application to collect point locations, images, and descriptive data on environmental stressors such as unlawful dumping [22]. This technique produced a fine-grained, street-level "spatial narrative" that captured risks and situation that are sometimes overlooked by official city authorities. Hayakawa et al. [23] describe the development of a "River Information Management System" in Japan, which includes a smartphone application that allows citizens to report issues such as illegal dumping directly to river administrators using photos and GPS coordinates. This crowdsourced data stream supplements official surveillance efforts, providing a broader observation net and allowing for faster response to emerging problems. Using this methodology in Lhokseumawe could validate expert-led field surveys while also supplementing the dataset with contextual information required for effective intervention planning. Besides, it can also help to establish a distributed, low-cost, and continuous monitoring network.

Beyond data collection, participatory methods can be used to co-create solutions. A method called Participatory Action Research (PAR) are successfully implemented in South Africa to engage the community members, NGOs, and municipal officials in a collaborative dialogue to identify not only the problems of illegal dumping but also its root causes and potential solutions [24]. This technique generates a strong sense of ownership. It guarantees that the initiatives that follow, such as new infrastructure, cleanup efforts, or educational programs, are culturally and practically relevant for the community they serve. This is in contrast to a purely technical site-selection process, which can occasionally result in community opposition due to a perceived lack of consultation.

Integrating these participatory approaches fundamentally redefines the nature of data" in urban planning. It validates qualitative, experiential knowledge as a legitimate and crucial input for what is often a quantitative spatial analysis. This challenges the traditional hierarchy of expertise, where the engineer or planner is the sole expert, and democratizes the planning process. This has direct, practical benefits.

Integrating these participatory methodologies establishes qualitative, experiential knowledge as a valid and necessary input for what is frequently a quantitative geographical analysis. This eliminates perception the traditional hierarchy of knowledge, in which the engineer or planner is the only expert, and democratizes the planning process. This has direct, practical advantages. For example, when a city planner in Lhokseumawe proposes a new WCP based on technical criteria such as road access and population density, people have their own reactions. However, if that same community has actively participated in mapping the problem of unlawful dumping in their neighborhood, as well as selecting and evaluating suitable places for a new WCP using a PGIS approach, the dynamic changes dramatically. The suggested facility is no longer an external solution imposed on them, but rather a collaborative response to a common need. This shift from conflict to collaboration improves the project's long-term survival and solves the underlying environmental issues that arise over the location of waste facilities planning.

Direct empirical research provides a strong theoretical and practical basis for the Lhokseumawe findings, proving that the lack of effective and easily accessible waste management facilities is the main cause of illegal waste disposal. It has been proven that there is a quantitative association between a lack of intermediate waste treatment facilities and an increase in the frequency of illegal dumping cases [25]. Besides, the availability of legal options overwhelmingly influences household trash disposal decisions [26].

Due to a lack of infrastructure, communities are forced to dump waste in the open, causing major public health and environmental risks. Households having easy access to formal collection services, such as curbside pickup or adjacent communal containers, are far less likely to engage in illegal dumping. This predicament is similar to that of many urban areas in Indonesia [27] and around the world [28] that do not have proper waste disposal facilities. This illustrates that the waste infrastructure gap is more than just a logistical failing; it is also an important problem of environmental justice and social fairness. It is emphasis supports Lhokseumawe's aim to increase the number and strategically situate WCPs, as the fundamental goal of such a network is to reduce the time, cost, and effort required for households to dispose of their trash lawfully and properly.

Socioeconomic variables at the community level are strong predictors of dumping. Wright et al. discovered that community-level indicators like high residential mobility (i.e., a transient population) and lower average levels of education and occupation were significant predictors of higher dumping rates [28]. Syafrudin et al. discovered that physical and demographic factors such as elevation and population density influence dumping patterns, with connections that differ by city [29]. These findings indicate that for Lhokseumawe, a social vulnerability analysis should be conducted and overlayed on the technical site-selection map. This will enable planners to foresee future issues in specific communities and customize community outreach, education initiatives, and facility design to meet the diverse needs of populations.

Complementing these patterns with GIS is crucial for vulnerability assessments. This vulnerability assessment will produce a risk map of vulnerability to illegal dumping. The criteria include land use, proximity to rivers and forests, and road network accessibility [30], [31]. This map will not only validate the need for WCPs in specific locations. However, it will also indicate areas requiring additional interventions, such as improved lighting, security, or physical barriers, which may be more reliable than constructing new WCPs. It has direct implications for the 44 proposed WCPs in Lhokseumawe; their success will depend not just on their existence, but on their perceived convenience and integration into the daily routines of residents. This might influence their location, operating hours, accessibility for different types of transport (e.g., handcarts vs vehicles), and cleanliness.

Finally, public perception and trust in the managing authority are indispensable. An innovative study by Du et al. [32] analyze web-based public discourse and revealed a significant disconnect between the priorities of the public and those of the government. The public was more concerned with long-term prevention strategies, while the government focused on solving immediate, visible problems like cleanup. This highlights a crucial need for the Lhokseumawe government to engage in transparent and sustained communication about its long-term prevention strategy—which the WCP network represents—to build public trust, secure buy-in, and encourage active participation in the new system. Without this trust, residents may view the new facilities skeptically or fail to understand their role in the broader strategy for a cleaner city.

Accurate mapping of illegal waste disposal sites is essential towards improving the waste management strategies, particularly surveillance and clean-up efforts. Future research aims to optimize the prevention of illegal dumping in solid waste management, including (1) involving the community in reporting illegal dumping directly from the mobile application, (2) exploring the potential of using drones in suburban area for waste management strategies, (3) predicting potential illegal dumping locations using machine learning, through socio-economic factors, land use and land cover, and historical data that has been conduct in this study.

IV. CONCLUSION

This project succeeded in its goal of developing a data-driven strategy for identifying optimal WCP locations by analyzing waste creation and mapping illegal dumping using Geographic Information Systems (GIS) and field surveys. The study concluded that Lhokseumawe City, which generates 530 m³ of waste daily, requires 44 strategically located waste collection points to improve service efficiency and manage waste effectively. The study gives a complete blueprint with optimal locations and designs for these facilities, resulting in a feasible plan to lessen the environmental impact of incorrect waste disposal and mitigate public health concerns. The combination of IoT technologies and public participation in future research is projected to improve trash management and city sustainability.

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