Scholarly Research Journal for Interdisciplinary Studies
Online ISSN 2278-8808, SJIF 2026 = 8.727
https://www.srjis.com/issues_data/293
Peer Reviewed & Refereed Journal, MAY-JUNE 2026, Vol- 15/95

TOWARDS DEMAND-DRIVEN URBAN WASTE INFRASTRUCTURE PLANNING: INTEGRATING WASTE GENERATION HOTSPOTS AND GIS-BASED LOCATION-ALLOCATION MODELLING IN PIMPRI CHINCHWAD MUNICIPAL CORPORATION, INDIA

Neha Dilip Bagul[#1] & Mrs. Jaspreet Kaur Chhabda [*2]
Department of Town and Country Planning
COEP Technological University, Pune, Maharashtra, India
Email- [1]nehabagul19@gmail.com

Paper Received On: 20 MAY 2026
Peer Reviewed On: 24 JUNE 2026
Published On: 01 JULY 2026

Abstract

The fast pace at which urbanisation has taken place in Indian urban centres has increased the spatial mismatch of solid waste generation and processing facilities, leading to operational inefficiencies, environmental degradation and public health risks. The study proposes an optimization framework for solid waste management (SWM) infrastructure in Pimpri Chinchwad Municipal Corporation (PCMC) which is an industrial city of Pune metropolitan region (PMR), Maharashtra, India with a projected population of 27.3 lakh and total waste generation of 1200–1300 metric tonnes per day (MT/day) in the year 2026. The study incorporates data on waste generation at ward level, population density mapping and road network analysis using Geographic Information Systems (GIS) to pinpoint the spatial hotspot of waste generation in the 32 wards of PCMC. A P-Median location-allocation problem is solved on a road network graph created from the OpenStreetMap (OSM) data to find the optimal placement of transfer stations and processing facilities to cover a given area with a minimum aggregate transportation distance. The current service delivered by three transfer stations and a single centralized landfill at Moshi was compared with the optimized outputs from the allocation, which identified significant gaps to service coverage, especially in wards along the periphery and in high-density wards. The results show that the method of allocation based on demand, with the help of GIS, significantly decreases the distances of transportation, distributes the load of infrastructure more uniformly and offers a scalable planning framework that is compatible with the goals of the Swachh Bharat Mission 2.0.

Index Terms: *GIS, solid waste management, location-allocation, P-Median model, waste generation hotspots, urban infrastructure planning, PCMC, demand-driven planning, network analysis.*

I. INTRODUCTION

A. Urban Waste Management Challenges

Municipal solid waste management (MSWM) is one of the most challenging issues of urban governance in the rapidly growing cities of developing countries. The growth of urban population in India at the rate of 3-3.5% annually has also resulted in an increase in waste generation at about 5% per year and has been a strain on the existing collecting, transfer and processing systems [1]. In India, the rate of waste generation has been estimated by the Ministry of Finance to be around 1.3% per year per capita (2009). The increasing requirements for SWM infrastructure are both in terms of quantity and spatial complexity, because the city itself grows spatially into the peri-urban areas, demanding infrastructure to be spread in a more complex and heterogeneous urban landscape.

The twin city of Pune and one of the fastest growing industrial urban centres of India, Pimpri Chinchwad Municipal Corporation (PCMC) is a prime example of these challenges. The solid waste generation rate in PCMC is 1,200 to 1,300 MT/day with an average of 0.44 kg per person per day [2] while the projected population in 2011 is 17,27,692 and it is estimated to be around 27.3 lakh by 2026 and 39.39 lakh by 2045. PCMC, despite having a structured door-to-door collection system, three transfer stations and a centralized processing and landfill facility at Moshi, still suffers from some inefficiencies including unequal waste accumulation in wards, poor source segregation, overloaded transfer stations and long and indirect transport routes resulting in high operational cost and carbon emissions [2].

B. Importance of Demand-Driven Infrastructure Planning

Traditional SWM infrastructure planning in Indian urban local bodies (ULBs) has largely been based on administrative boundaries and fixed assets deployment without considering spatial distribution of waste generation as a key planning input. This has led to infrastructure that does not reflect the true demand – some central wards with high population and activity densities are over-served, while peripheral wards with high numbers of in-migrants are chronically under-served [3].

A demand-driven approach reframing waste generation hotspots as the building blocks of infrastructure planning. Ward level mapping and quantification of waste demand can then be used to strategically locate facilities to match demand patterns, ensuring that waste services are distributed equitably, efficiently and cost effectively. This is particularly relevant in the background of governing rules on waste management like Solid Waste Management Rules 2016 laying emphasis on scientifically planned siting of facilities and Swachh Bharat Mission

2.0 which emphasised on data-led planning and decentralisation of processing. Forecasting waste generation and utilizing pro-active planning is essential to avert the looming problem of infrastructure in PCMC that is expected to reach 3,000 MT/day by 2046.

C. GIS and Location-Allocation Applications in SWM

The incorporation of Geographic Information Systems (GIS) in SWM planning has become increasingly acknowledged, as these systems enable spatial analysis that is needed to model waste demand, assess infrastructure accessibility and optimise the location of infrastructure facilities [4]. The use of GIS-based techniques has been shown in various studies in India and globally to be useful in a number of critical functions in SWM such as waste generation estimation [5] and route optimization [6] and facility siting using multi-criteria decision analysis [7]. The location-allocation model, especially the P-Median formulation, has become the most popular optimization model for SWM facility planning due to its ability to minimize sum of weighted distances between demand points and their assigned facilities [8].

Most of the current research is based on either the landfill siting problem using suitability analysis or on the collection route optimization problem as an isolated problem, however. The question of where a transfer and processing facility should be located in relation to spatial waste demand patterns has largely been ignored and few studies have combined the concepts of waste generation hotspot mapping with network-based location-allocation modelling [9].

D. Research Gap

The literature shows that although location-allocation models for landfills using GIS are widely observed, there are few studies that address the issue of planning and locating transfer stations and processing facilities over a road network in a rapidly urbanizing Indian city with a quantified waste generation hotspot. Most studies currently available only focus on the overall demand of waste or apply population proxies, not accounting for waste generation rates at a ward level based on the municipal data. Additionally, few studies have directly compared the distribution of existing facilities with the distribution of an optimized facility to measure the inefficiency of the current facility distribution.

II. LITERATURE REVIEW

A. GIS Applications in Solid Waste Management

GIS has come a long way in two decades in SWM from mere spatial mapping to advanced optimisation models. Deswal and Laura [4] examined the applications of GIS in Indian MSWM and emphasized its role in waste generation estimation, placement of temporary bins, route optimization and selection of dumpsites. They found that GIS-based approaches save time and money in the process of SWM planning and deliver digital data infrastructure for ongoing monitoring. In a similar approach, Karadimas and Loumos [5] created a GIS model for the estimation of waste production in Athens, separating residential and commercial wastes and showing that the number of required bins could be reduced by 30% by the spatial placement of bins, leading to substantial savings in the collection costs.

B. Waste Generation Mapping and Demand Estimation

Spatial estimates of waste generation are key to demand-driven infrastructure planning. In Dhanabad, India, Khan and Samadder [3] showed that their system of assigning bins at road intersections based on population density and waste generation rates and they used GIS-based vehicle routing achieved an efficient system with 726 bins and 66 optimized routes. Hannan et al. [9] surveyed solid waste collection optimization objectives and constraints, stating that the combination of GIS, GPS, RFID and sensor technologies provides dynamic real-time demand management. In India, Sutar et al. [10] used GIS to optimise waste collection routes in rural areas of Mahalung, Solapur, showing how an optimised spatial plan of waste collection routes can benefit even small area settlements over an ad hoc system to dispose of the waste.

C. Location-Allocation Models for SWM Facilities

The mathematical tool used to decide on the optimal number of facilities and their locations with respect to demand is called location-allocation modelling. In designing waste transport routes for Asansol Municipality that minimize waste cost, Ghose et al. [6] used the NETWORK module of Arc/Info GIS and resulted in significant savings compared to the current system. Ağacsapana and Cabuk [11] applied weighted overlay GIS analysis to determine the optimal waste transfer station sites in Eskişehir, Turkey, where only 1.1% of the study area was determined to be suitable for the station siting based on both environmental and accessibility criteria. Their research highlighted the need for taking spatial limitations into consideration, along with optimization.

D. P-Median and Network-Based Optimization

The most popular location-allocation model for SWM facilities is the P-Median model that minimizes the sum of weighted distance between demand and facilities. In the Municipality of Nikea, Athens, Chalkias and Lasaridi [12] used network-based P-Median approach where 17% of the collection time was saved and 12.5% of the travel distance saved by both combined bin relocation and route optimization. Kwikima and Ngole [13] used P-Median and P-Center models via ArcGIS Network Analyst to simulate the waste collection coverage in Sumbawanga, Tanzania, projecting a 90% increase in coverage from 40% with 25% reduction in the use of fuel. Singh and Behera [14] used the Dijkstra's algorithm-based GIS optimization for Transport Route Selection in Kanpur; the minimization of haul distance shows that the optimal routes can be selected in order to achieve significant reduction in haul distance compared to the fixed routes.

E. Infrastructure Accessibility and Coverage

A major performance indicator of SWM system is infrastructure accessibility which means the ability of waste generation system to link with the facilities within acceptable distance. Amirhossein et al. [15] used GIS-based network analysis to highlight the ability to achieve route length savings of up to 22% in Ipoh, Malaysia, thereby freeing up the resources of the collection service for the recycling of waste materials. Nguyen-Trong et al. [16] used GIS and mixed integer linear programming (MILP) to optimize waste transportation and combined with agent-based modelling found that cost savings of static modelling could be obtained, with an 11.3% reduction in cost in Hagiang, Vietnam. The results show that the network-based optimization is always cheaper and more coverage than the fixed-route systems and this conclusion hold true regardless of the case.

F. Research Gap Summary

The literature reviewed indicates that GIS-based location-allocation modelling can be used effectively for the optimization of SWM facilities. Yet, there is a lack of studies that: (i) incorporate municipal waste generation data at the ward level as the primary demand input as opposed to population proxies; (ii) use the P-Median model for the particular purpose of allocation of transfer stations and processing facilities in rapidly urbanizing Indian cities; and (iii) explicitly compare the outcomes of the optimized allocation of transfer stations and processing facilities with the existing system to quantify the improvement. This study tackles all three gaps with respect to PCMC.

III. STUDY AREA AND EXISTING WASTE MANAGEMENT SCENARIO

A. Study Area Profile

Pimpri Chinchwad Municipal Corporation (PCMC) is located at 18°37' N, 73°48' E in the Pune Metropolitan Region, Maharashtra, India. It is the twin city of Pune and one of the fastest-growing industrial urban centres in the country, encompassing IT, automobile, pharmaceutical and manufacturing industries. PCMC covers a municipal jurisdiction of approximately 181 km^2, divided into 32 administrative wards across 8 administrative zones (A through H). As per the 2011 Census, PCMC's population was 17,27,692, projected to reach approximately

24,03,860 in 2025 and 39,39,000 by 2045. The 2026 projected population used in this study is

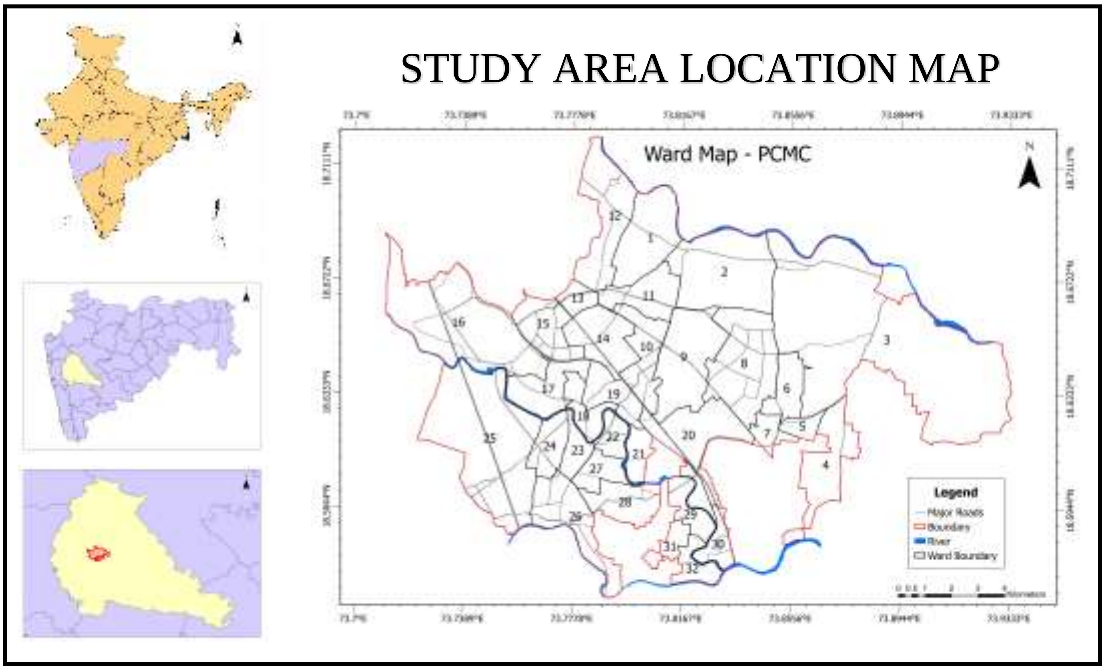

Figure 1 Study Area Location Map PCMC Ward Boundaries and Administrative Zones

27.3 lakh.

PCMC's rapid urbanization has led to diverse land uses including dense residential zones, large industrial estates, mixed-use commercial corridors and rapidly expanding peri-urban settlements. This spatial heterogeneity generates highly variable patterns of waste generation across wards, making uniform infrastructure deployment inefficient and necessitating a demand-driven planning approach.

B. Existing Waste Management System

PCMC operates a solid waste management system that includes door-to-door collection using a fleet of approximately 404 vehicles (2022–23), comprising compactors, chhota hathis, tippers and ghanta gadis. Collected waste is transported to three operational transfer stations at Kasarwadi, Gavlimatha and Kalewadi, from where it is moved to the centralized processing and disposal facility at Moshi, located in the northeastern part of the jurisdiction. The Moshi facility has an estimated composting capacity of ~300 tonnes per day (TPD) and handles approximately 1,200 TPD for landfilling.

The amount of waste each person generates is 0.44 kilograms per day. The total amount of waste generated every day is around 1,200 to 1,300 tons. By the year 2026 the total amount of waste generated will be around 1,200 to 1,300 tons, per day. After 2036 waste generation will increase fast because the population will be growing faster. Waste is made up of two types:

waste that breaks down easily which is about sixty percent and dry waste that can be recycled or does not break down which is about forty percent.

Table I Existing Solid Waste Infrastructure in PCMC

Facility	Type	Count	Capacity / Status
Transfer Station	Intermediate	3	~600 T/day combined (Kasarwadi, Gavlimatha, Kalewadi)
Composting Facility	Processing	1	~300 TPD (Moshi)
Sanitary Landfill	Disposal	1	~1,200 TPD (Moshi) nearing capacity

Key challenges of the existing system include, centralization of processing around a single Moshi facility creating long transport hauls; uneven spatial distribution of transfer stations with coverage gaps in peripheral and western wards; absence of Material Recovery Facilities (MRFs) and bio-methanation plants creating landfill overdependence; and overlapping and irregular collection routes indicating absence of route optimization.

IV. MATERIALS AND METHODS

A. Data Collection

The study combines various spatial and attribute data sets provided by PCMC as well as from the national agencies and open data platforms. Population censused at ward level in 2011 and projected to 2025-26. The location-allocation model's primary demand input was ward-wise daily waste generation data directly obtained from PCMC's Health Department. Road network was obtained from OSM data and was pre-processed in ArcGIS to generate the network dataset that could be used for impedance-based routing. The ward boundary shapefiles were given by the GIS cell of PCMC.

TABLE II Spatial Data Layers Used in the Study

Data Layer	Source	Format	Use in Analysis
Ward Boundaries	PCMC GIS Cell	Shapefile	Spatial unit of analysis
Population (2011 + projections)	Census of India / PCMC	Tabular / Shapefile	Demand estimation
Waste Generation (ward-wise)	PCMC Health Department	Tabular	Primary demand input

Road Network	OpenStreetMap (OSM)	Shapefile / Network Dataset	Network analysis & routing
Existing SWM Facilities	PCMC Administration	Point Shapefile	Baseline system evaluation
Land Use/Land Cover (LULC)	Sentinel-2 Satellite Imagery	Raster	Context mapping

B. Waste Demand Estimation

Ward-level waste demand (WDI) is estimated as:

WDI = Pi × r

Where Pi is the ward population and r is the per capita waste generation rate (0.44 kg/person/day, derived from PCMC data). The resulting ward-wise WDI values are aggregated to yield a total daily demand of 1,200–1,300 MT/day across PCMC's 32 wards for the 2026 scenario. Ward centroids weighted by their WDI values serve as demand points in the location-allocation model.

Wards are classified into four waste demand categories based on their daily waste generation:

TABLE III Waste Generation Demand Classification by Ward

Demand Class	**Waste Generation (T/day)**	**Implication**
Low Demand Zone	< 25 T/day	Sparse population; peri-urban or low-density wards
Moderate Demand Zone	25 – 32 T/day	Medium density residential / mixed-use wards
High Demand Zone	33 – 40 T/day	Dense residential or commercial wards
Very High Demand Zone	> 40 T/day	High-density urban core; immediate infrastructure priority

C. Waste Generation Hotspot Mapping

Waste generation hotspots can be identified by basing on the WDI classification of wards to the demand zone using the threshold values in Table III and mapping the WDI values onto the

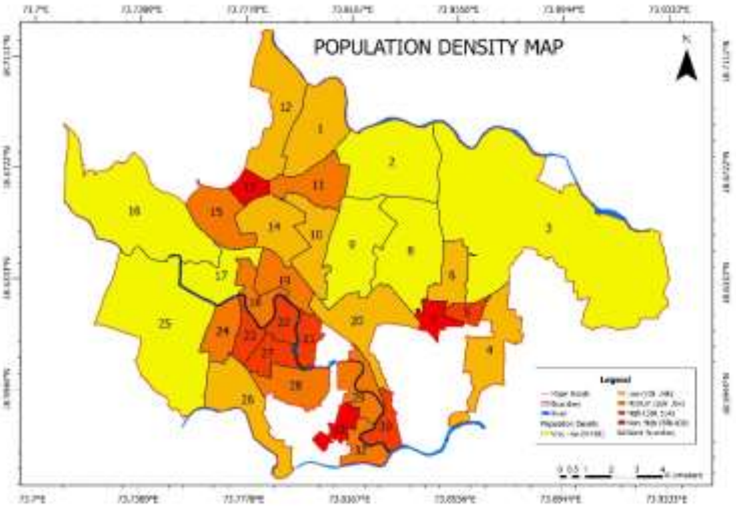

Figure 2 Waste Generation Hotspot Map Ward-level Demand Classification across PCMC (Low / Moderate / High / Very High)

ward polygon layer of PCMC. This hotspot map can then be used to clearly identify waste hotspots in spatial terms, which can be used as high-priority demand centres in the planning of facilities. This map is the main visual and analytical data to feed the location-allocation model and, therefore, will help ensure that the proposed locations for facilities are in response to the spatial demand patterns, as opposed to administration.

D. Network Dataset Preparation

The road network dataset is created from the OSM road data layers within PCMC jurisdiction. Road segments are categorised by a hierarchy (highway, arterial, collector, local) and an impedance (metres) is given to them. The network constraints include one way restrictions, road closures and minimum road width (per CPHEEO norms ≥ 9 m) restrictions. The network data created in ArcGIS Network Analyst can be used for shortest path routing and service area analysis as part of an accessibility assessment.

E. Location-Allocation Modelling (P-Median)

The P-Median location-allocation model is applied using ArcGIS Network Analyst's Location-Allocation tool with the 'Minimize Impedance' objective, which is equivalent to the classical P-Median formulation [8][17]. The model minimizes the total weighted impedance (distance) between demand points and their assigned facilities:

Minimize $\boldsymbol{Z = \Sigma_i \Sigma_j w_i \cdot d_{ij} \cdot x_{ij}}$

Subject to:

$\Sigma_j x_{ij} = 1$ ∀i *(each demand point assigned to exactly one facility)*

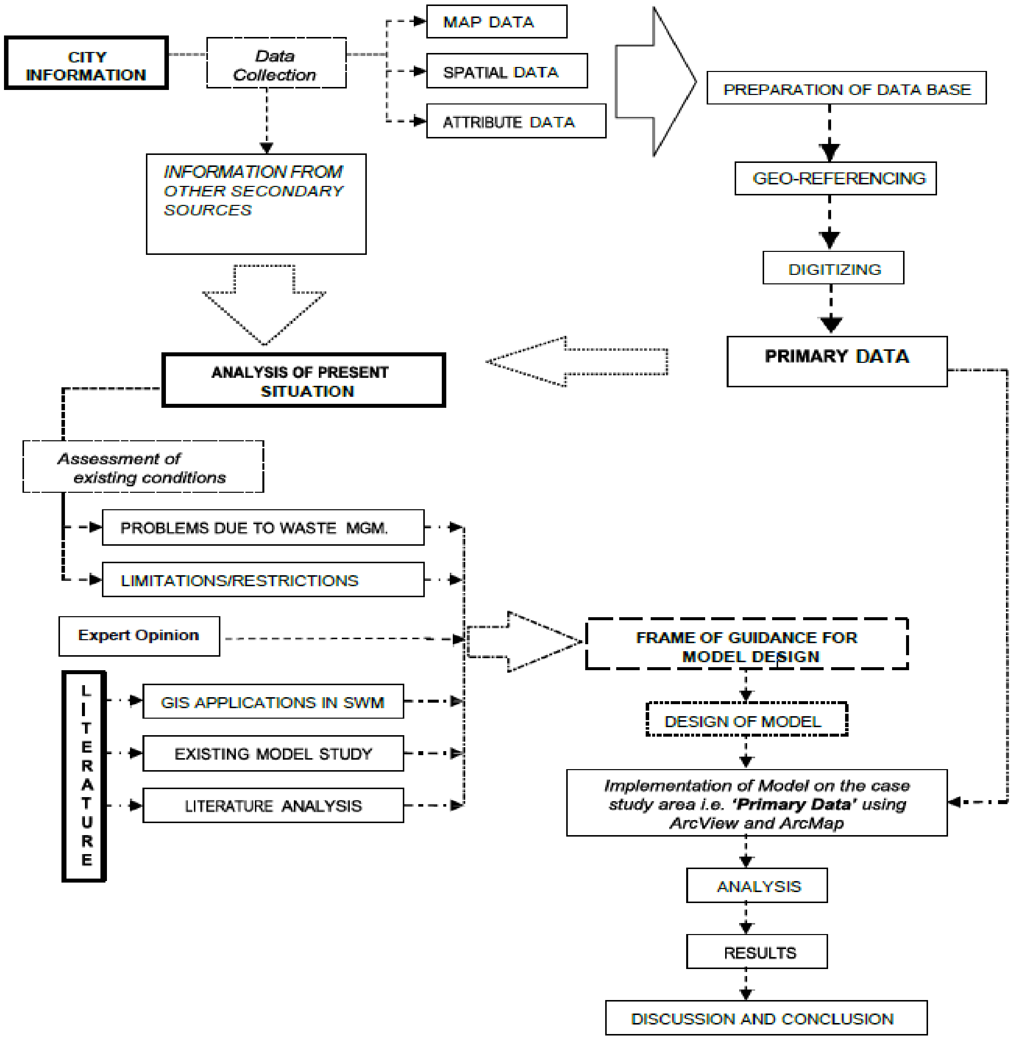

Figure 3 GIS-Based Methodology Framework Data to Demand to Allocation

$x_{ij} \leq y_j \ \forall i,j$ *(demand assigned only if facility is open)*

$\Sigma_j \, y_j = p$ *(exactly p facilities selected)*

Where w_i is the waste generation weight of demand point i (T/day), d_{ij} is the road network distance between demand point i and candidate facility j, x_{ij} is a binary variable (1 if demand i is assigned to facility j) and y_j is a binary variable (1 if facility j is open). The number of facilities to open (p) is determined by CPHEEO norms: 1 transfer station serves 2–5 lakh persons with a throughput of 200–500 T/day.

Candidate facility sites are extracted from the suitability analysis outputs, filtered to include only locations meeting all regulatory hard constraints specified in SWM Rules 2016 and the CPHEEO Manual (minimum 500 m buffer from residential areas, 200 m from water bodies, road width ≥9 m). Ward centroids weighted by daily waste generation serve as demand points. The model is run for p = 5 transfer stations (existing 3 + proposed 2 new) for the 2026 scenario.

V. RESULTS AND DISCUSSION

A. Spatial Distribution of Waste Generation

A comparison of the waste generation figures across PCMC's 32 wards will clearly show that the generation of waste varies significantly across the city. On the lower end, there are less populated areas such as Ward 8, which produce approximately 20 tonnes per day and busier wards, such as Ward 11, with over 1,07,605 people producing up to 49 tonnes per day. In 2026, the city is set to produce a total of 1200-1300 MT of waste per day or approximately 0.44 kg per person, which is typical for large Indian cities.

The future numbers are only going to continue to rise. Waste generation is expected to go over 1200-1300 MT/day this year and will touch around 3000 MT/day by 2046 when PCMC's population is reaching the milestone of 40 lakh people. The systems that can grow incrementally are necessary when that kind of growth occurs and not having to do a complete overhaul and rebuild.

B. Waste Generation Hotspots

The 32 wards have been categorised into four groups according to the amount of waste they produce to understand the pressure of each ward. More than 40 tonnes per day are generated in 6 wards - these are Wards 11, 12, 16, 19 and 22 - and should be the top priority when planning new infrastructure. There are also another 11 wards in the 'High Demand' category producing 33 to 40 tonnes per day. These high-demand wards are concentrated in the central-western areas of the city (Zones A, B and F) and the lower-demand wards are more on the outskirts of the city (Zones D and H).

An obvious problem is the separation between the site of problem and the site of the facilities to handle it. The three PCMC transfer stations in the city are clustered in the south-central area of the city, namely, Kasarwadi, Gavlimatha and Kalewadi. Western Zone F and eastern Zone

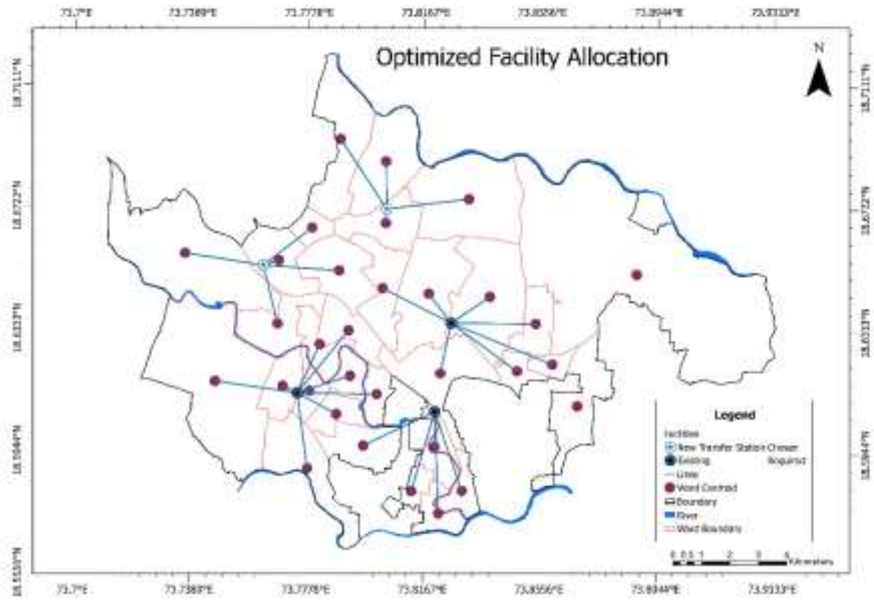

Figure 4 Location-Allocation Output Map Existing vs. Optimized Transfer Station Distribution with Demand Allocation Lines

E, which have high demand, are without any infrastructure to receive their waste that can accommodate the growth. This leaves longer routes for waste trucks from outer wards and an inequitable distribution of waste load among the three stations that are available.

C. Location-Allocation Results

The P-Median model, run for p = 5 transfer stations on the PCMC road network, selects two new facility locations in addition to the three existing stations. The model assigns all 32 ward centroids to their nearest (impedance-minimizing) transfer station while ensuring no station exceeds its throughput capacity of 300–500 T/day. The optimized allocation results in significantly shorter allocation distances compared to the existing system:

TABLE IV Comparison of Existing and Optimized Transfer Station Allocation

Parameter	Existing System	Optimized System	Improvement
No. of Transfer Stations	3	5	+2 new stations
Spatial Coverage	Central-south clustered	Distributed across all zones	Balanced
Avg. Haul Distance (ward centroid to TS)	Long, indirect routes	Short, direct routes	Substantially reduced
Load Distribution	Overloaded on 1–2 stations	Even across 5 stations	Improved
Wards within Effective Service Range	Limited (central wards)	All 32 wards	Full coverage
System Efficiency	Low	High	Significantly improved

The two new transfer stations proposed by the model are located in Zone D (northeastern area, serving Wards 25, 26, 28, 29 combined waste load ~129 T/day with no existing TS within 5 km) and Zone B/G/H (western area, serving Wards 22, 23, 27, 30, 31, 32 combined ~162 T/day). Ward 31 is the most critically underserved, with a population of 83,692 and no nearby transfer station, making it a high-priority allocation target.

D. Infrastructure Accessibility Analysis

Service area analysis using 3 km road network buffers around existing transfer stations reveals that a substantial number of high-generation wards particularly in the western and southern periphery of PCMC fall entirely outside effective service range. This forces collection vehicles to undertake long, indirect hauls to the nearest station, contributing to the current system's inefficiency in terms of both time and fuel consumption.

The optimized system extends effective service coverage to all 32 wards. The two new stations are sited on road-accessible, suitable land parcels identified through the suitability analysis, meeting all SWM Rules 2016 buffer requirements (≥500 m from residential areas, ≥200 m from water bodies, road width ≥9 m). The resulting allocation lines in the model output are shorter and more direct, indicating improved accessibility throughout the jurisdiction.

TABLE V Infrastructure Accessibility Existing vs. Optimized System

Indicator	Existing System	Optimized System
Wards with TS within 3 km (road network)	~12–15 central wards	All 32 wards
Avg. allocation distance	Long (indirect routing)	Short (direct routing)
Load per transfer station (T/day)	~400+ T (overloaded)	~260 T (balanced)
Coverage gap wards	Western + peripheral zones	None
Alignment with CPHEEO norms	Partial	Full compliance

E. Planning Implications

The results have some relevant policy implications for PCMC and other Indian cities experiencing similar high growth rates. One such benefit is that, of course, building around real hotspot data isn't building in the areas where it's convenient to administer; it's building in the places where it's truly needed, so as to avoid building too much in the wrong place, or too little in the right place and to avoid the cost and time of building where it's not needed. Another important aspect of the P-Median model is that it provides decision makers with a consistent and repeatable approach to selecting facility locations, not only to ensure that the math works out, but also to ensure that facility locations may be explained and justified in public and in accordance with national guidelines on solid waste management.

This phased rollout also has a lot of sense of practicality. The city is not embarking on a massive building program that it will have to catch up on in the years to come but is building capacity by adding two transfer stations in phase one (2025-2030) and two more in phase 2 (2031-2038). The benefits are as tangible on the day-to-day operational side. The reduction in the number of miles that vehicles have to travel daily across a facility reduces the total number of miles that vehicles travel daily, which directly impacts on lower fuel costs, reduced wear on trucks and lower emissions. A more balanced load distribution at the five stations also increases the overall resilience of the system, should one facility experience problems it doesn't cause the rest of the system to collapse. Perhaps most importantly, the GIS project created for this study is not an isolated, one-off project. This can be updated with new waste data as it becomes available and re-run as the need arises to revisit decisions about facilities.

VI. CONCLUSION

This study has demonstrated the value of an integrated, demand-driven GIS framework for optimizing solid waste management infrastructure in rapidly urbanizing Indian cities. Applied to PCMC, the framework successfully integrates ward-level waste generation hotspot mapping with a P-Median location-allocation model on the road network to identify optimal transfer station locations that minimize aggregate transportation distance while ensuring equitable spatial coverage across all 32 wards.

The analysis reveals that PCMC's existing three-station system is spatially clustered in the south-central zone, leaving high-generation wards in the western and peripheral areas chronically underserved and imposing unnecessarily long haul distances on collection vehicles. The optimized model identifies two new transfer station locations one in Zone D (northeastern) and one in Zone B/G/H (western) that together extend effective service coverage to all wards, balance load distribution and substantially reduce average allocation distances.

Five key conclusions emerge from this study:

1) Waste generation in PCMC is spatially concentrated, with Very High Demand wards generating up to 49 T/day and predominantly located in central-western zones.
2) Waste generation hotspots, when used as weighted demand inputs, provide a more accurate basis for facility allocation than population proxies alone.

3) The P-Median location-allocation model on road networks systematically improves accessibility, reduces haul distances and balances infrastructure load compared to the existing system.
4) Demand-driven planning aligned with SWM Rules 2016 and CPHEEO norms produces a spatially optimized, cost-effective and regulatory-compliant infrastructure plan.
5) The GIS framework developed is replicable and scalable, offering a practical decision-support tool for PCMC and other rapidly urbanizing Indian urban local bodies.

Future research should extend this framework to incorporate real-time waste generation data from smart bin sensors, dynamic vehicle routing optimization and integration with carbon emission accounting to support PCMC's sustainability planning under Swachh Bharat Mission 2.0 and Smart City programme objectives.

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