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Smart Waste Management For Zero-Waste Urban Future: Gis-Enabled Optimization Of Municipal Solid Waste Collection

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Abstract
Oum El Bouaghi, Algeria, faces significant inefficiencies in household waste management, including fragmented collection routes, vehicle incompatibility, and organisational weaknesses, resulting in high operational costs and service gaps. This study aimed to optimise waste collection through digital transformation, focusing on route reorganisation, fleet rationalisation, and infrastructure harmonisation to reduce costs and improve service quality. A mixed-methods approach was employed, combining spatial analysis (GIS), stakeholder interviews, field observations, and operational data review. Diagnostic phase analysis identified inefficiencies, followed by an optimisation scenario featuring route restructuring, vehicle reselection, and container redistribution. Optimisation reduced annual operational costs by 36% (47.6 million DA), primarily through streamlined personnel, strategic vehicle deployment ($24m^3/18m^3/12m^3$ compactors), and minimised non-productive travel. Collection efficiency increased by 33% (average yield: 1.82 tonnes/hour), while optimised sectorization enhanced spatial coverage. Integrated logistical restructuring, supported by GIS, significantly enhances cost efficiency and service reliability in resource-constrained urban settings. The savings enable reinvestment in sustainable urban development, demonstrating scalability for similar mid-sized cities in transitional economies.

Keywords: *Municipal solid waste management, Route optimisation, GIS application, Cost efficiency, Vehicle fleet management, Developing cities.*

INTRODUCTION:

Effective household waste management (HWM) constitutes a fundamental pillar of sustainable urban development, with profound implications extending far beyond basic sanitation [1,2]. Inefficient systems pose significant threats to public health through disease vectors and environmental contamination, degrade the quality of living environments via littering and visual pollution, and contribute substantially to broader ecological burdens, including greenhouse gas emissions from landfills and soil/water resource degradation [3,4]. Consequently, optimising HWM services represents a critical priority for municipalities globally, demanding solutions that balance operational efficacy, environmental responsibility, and economic viability [5]. The challenges of municipal solid waste management (MSWM) are particularly acute in rapidly urbanising regions of the Global South, where infrastructure development often lags behind population growth and consumption patterns. Urban centres in Algeria and similar contexts face a triple burden: escalating waste generation rates, limited fiscal and technical resources, and increasing regulatory pressures to meet sustainability targets [6]. In sub-Saharan Africa—a region with comparable developmental challenges—studies reveal that waste generation is projected to increase by 140-180% by 2050, exacerbating pressure on already strained collection systems [1]. The organic fraction dominance (60-70% of total waste stream) in developing cities creates distinctive management challenges, including rapid decomposition, leachate production, and potent methane emissions when improperly landfilled [6]. These factors converge to create complex logistical, environmental, and public health challenges that demand context-specific solutions rather than direct technology transfers from Global North models. Recent technological advancements have catalysed a transformative potential in reimagining conventional waste management paradigms. Innovative waste technologies (SWT)— encompassing Internet of Things (IoT) sensors, artificial intelligence (AI)-driven analytics, geographic information systems (WebGIS), and business intelligence platforms—offer unprecedented capabilities for optimising collection routes, monitoring bin fill-levels in real time, and dynamically allocating resources [7,8]. IoT-enabled systems demonstrate particular promise, with sensor networks providing real-time operational intelligence that transitions waste collection from fixed schedules to demand-responsive operations, reducing collection frequencies by 20-30% while eliminating overflow incidents [7,9]. Blockchain applications further enhance transparency in reverse logistics chains, creating verifiable trails from generation to recovery or disposal—a critical feature for regulatory compliance and circular economy transitions [9]. The integration of these technologies facilitates a systemic optimisation framework where data analytics inform strategic decisions across the waste management hierarchy—from prevention and reuse to recovery and disposal. When implemented within coherent governance structures, digital tools enable municipalities to overcome traditional barriers of fragmented data, operational opacity, and reactive management [10]. Notably, the adaptive variable neighborhood search (AVNS) heuristic developed for heterogeneous electric vehicle routing in Samsun, Turkey, demonstrated 22-40% efficiency gains in collection logistics while accommodating multi-compartment vehicles, split deliveries, and waste stream-vehicle compatibility constraints [11]. Such approaches highlight the potential for algorithmic optimisation to address complex real-world constraints prevalent in mid-sized cities. Despite proliferating research on smart waste technologies, significant knowledge gaps persist regarding their implementation in medium-sized Algerian cities characterised by unique urban morphologies, institutional frameworks, and socio-cultural contexts. Most documented implementations focus on megacities or highly developed economies with substantial technological infrastructures and financial reserves [1,12]. The transition toward zero-waste cities—defined as urban models eliminating landfill disposal through circular economy principles—requires radical sociotechnical innovation where digital governance plays an orchestrating role [13,14]. However, studies explicitly addressing this transition in North African intermediate cities remain scarce. Research by Guo (2025) emphasises that successful digital transformation necessitates a "multi-stakeholder approach involving government support, technological innovation, and citizen engagement" [15]—a framework requiring validation in specific contexts like Oum El Bouaghi. Furthermore, the regulatory landscape in Algeria presents distinctive opportunities and constraints. The national solid waste strategy emphasises waste valorisation and landfill diversion, yet implementation at the municipal level encounters obstacles including institutional fragmentation, limited technical capacity, and budgetary constraints [3]. Recent assessments of MSWM systems in sub-Saharan Africa underscore that sustainability evaluations must incorporate "socioeconomic realities and infrastructural constraints" rather than applying standardised Global North indicators [1]. This necessitates contextually grounded research examining how digital transformation can be sequenced and scaled within existing institutional and infrastructural parameters.

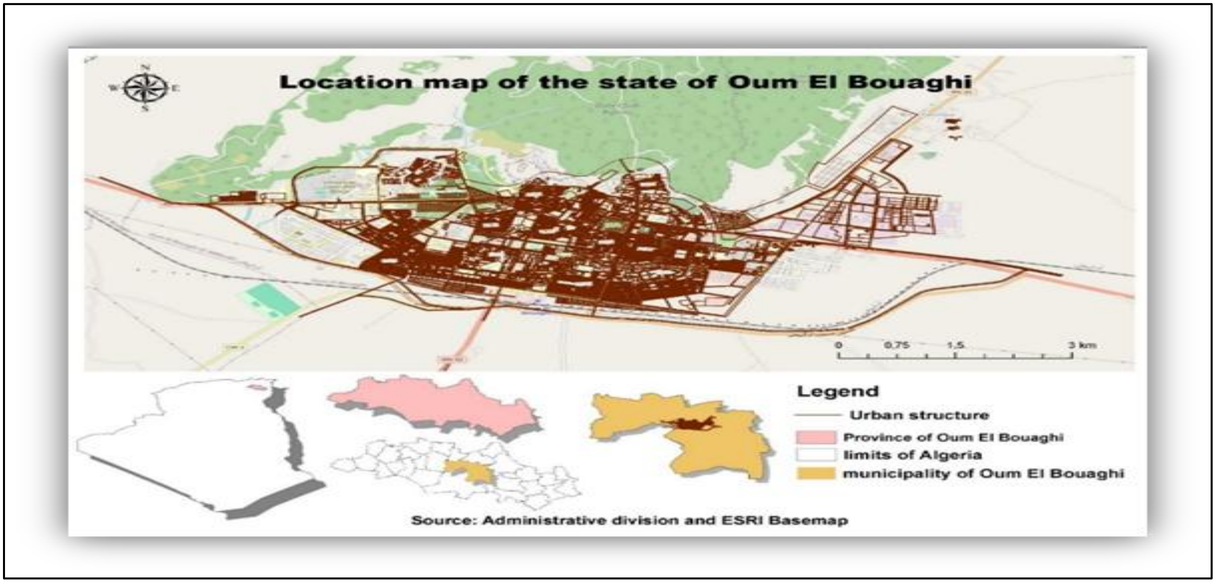
The city of Oum El Bouaghi, Algeria, faces significant challenges in waste management, common in many urban centres of developing economies, where rapid urbanisation strains existing infrastructure. A diagnostic study identified critical inefficiencies in waste collection services, including poorly designed routes, misaligned vehicle fleet deployment, and high operational costs that drain scarce municipal resources from other essential urban projects. Specifically, the city's existing routes were inefficient, characterised by excessive travel distances, poor coverage density, and suboptimal sequencing, leading to fuel wastage, vehicle wear and tear, and extended collection times. Additionally, the vehicle fleet's suitability and utilisation did not align with the city's waste generation patterns, topographic challenges, and road network characteristics. Although route optimisation and fleet rationalisation are well documented in solid waste management logistics, their application in mid-sized Algerian cities like Oum El Bouaghi remains underexplored. This knowledge gap is evident in the scarcity of case studies quantifying the impact of such optimisation strategies in specific socioeconomic, geographic, and infrastructural contexts. To address these issues, an optimisation project was implemented, focusing on redesigning collection routes to minimise travel distances, harmonising schedules and zones, and selecting vehicles tailored to local conditions, including narrow streets and traffic patterns. The project aimed to reduce operational costs, such as fuel, labour, and maintenance, while improving service quality and reliability. This article presents a detailed examination of the project, including the methodology for route optimisation and vehicle selection, an analysis of cost reduction and service efficiency outcomes, and a discussion on the broader implications of the findings, such as the potential for redirected funds to support other urban development priorities. The study offers valuable insights into creating cost-effective, efficient waste collection systems in similar urban environments.

2. METHODOLOGY

This study employed a mixed-methods case study approach to analyse and optimise the household solid waste management system in Oum El Bouaghi, Algeria. Conducted over 12 months (January-December 2023), the research comprised two sequential phases: (1) a comprehensive Inventory and Diagnostic of the current waste management system, and (2) Development of an optimisation scenario.

2.1. Study area

The study focused on Oum El Bouaghi, capital of Oum El Bouaghi Wilaya (province). Created in 1974 and revised in 1984, the wilaya is situated in Algeria's Constantine Highlands (Figure 1).



Source: Administrative division and ESRI Basemap

Figure 1. Geographical location of the town of Oum El Bouaghi

The urban centre (population approximately 120,000) faces significant waste management challenges due to rapid urbanisation. Waste management is overseen by municipal authorities, with operational execution by EPIC "AMUR," serving 13 designated collection sectors (Figure 2).

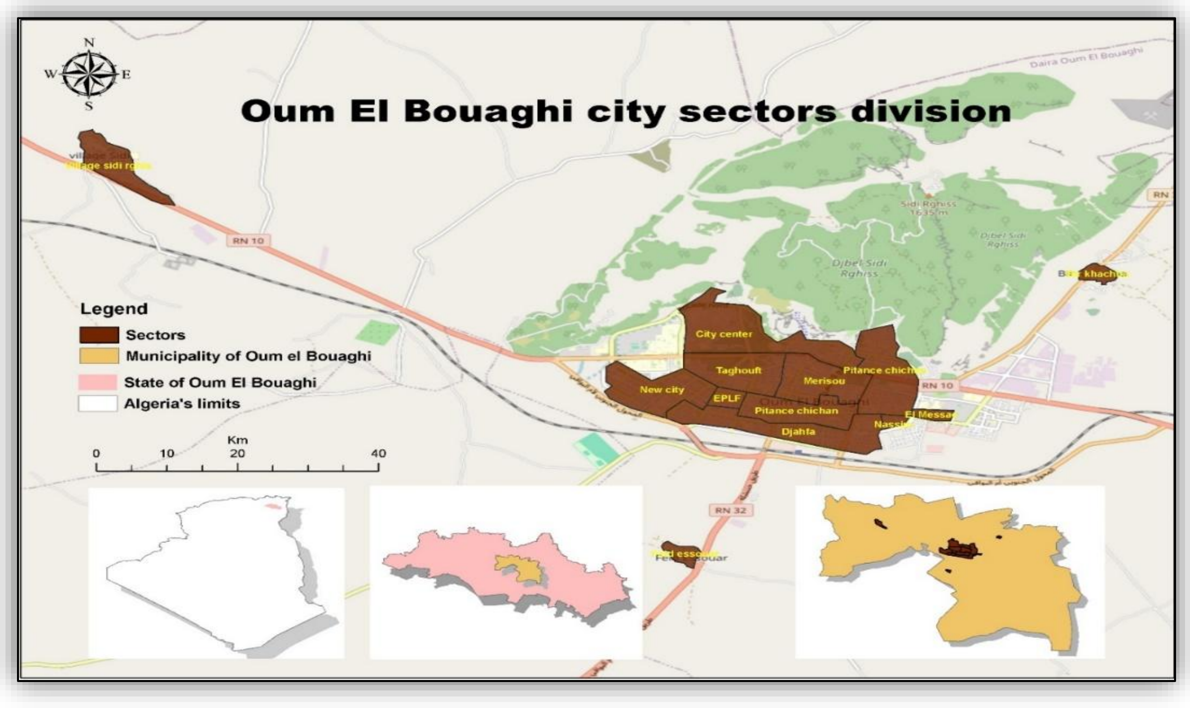


Figure 2. Division of the city of Oum el Bouaghi into sectors

2.2. Phase 1: Inventory and Diagnostic

This phase established a technical, organizational, and financial baseline through triangulated data collection.

2.2.1. Data Categories

Contextual Data: Housing typology was classified via urban planning documents and field surveys;

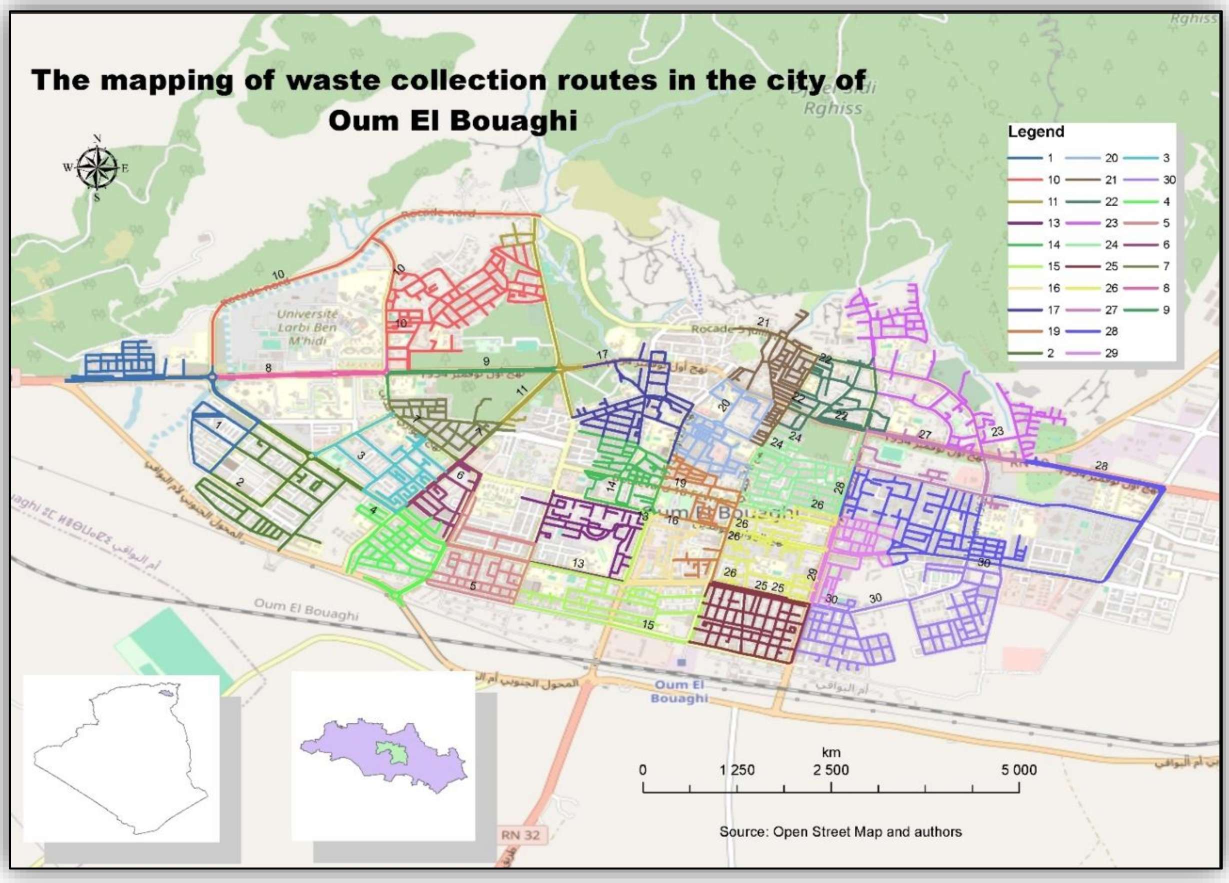
demographic data originated from municipal census records; environmental factors including road networks and topography were documented through GIS analysis of municipal base maps.

Waste Management Data: Technical infrastructure inventories covered vehicle fleet specifications and container distribution; operational parameters included GIS-tracked routes and timed collection cycles; waste quantities were derived from weighbridge records; collection methods were mapped through georeferenced surveys.

2.2.2. Data Collection Methods

Semi-Structured Interviews: Fifteen purposively sampled stakeholders across EPIC AMUR's hierarchy (directors, department heads, sector managers, operational staff) and municipal departments were interviewed following a predefined protocol (Supplementary Material S1), with sessions averaging 45-60 minutes and audio-recorded with consent.

Structured Field Observations: Thirty collection cycles across all 13 sectors were observed using standardized checklists, while spatial data (routes, collection points) were recorded with Garmin GPSMAP 64s units; Figure 3 illustrates representative collection circuits documented during observations.



Source: Open Street Map and authors

Figure 3. The waste collection circuit of the city of Oum el Bouaghi

Document review

Operational records (fleet logs, personnel rosters, collection schedules), financial documents (2022 budgets), waste tonnage reports, and urban base maps were obtained from EPIC AMUR and municipal departments.

GIS data integration

All spatial data (sector boundaries, collection points, routes, infrastructure) was compiled and analysed in QGIS v3.28, with municipal base maps georeferenced to support spatial analysis.

2.2.3. Data analysis (diagnostic phase)

The diagnostic phase employed a multi-method analytical framework to synthesise quantitative and qualitative data into a comprehensive assessment of the municipal solid waste management system. This integrated approach ensured specific research objectives and diverse data types were addressed systematically.

Descriptive statistical profiling

Quantitative operational data, encompassing waste tonnage, vehicle specifications, route durations, staffing levels, and container counts, underwent rigorous descriptive statistical analysis using SPSS Statistics v28. Key metrics calculated included means and standard deviations for continuous variables (e.g., average daily waste collected per sector, average route duration), frequencies and percentages for categorical variables (e.g., distribution of collection frequencies, vehicle type composition), and ranges with minimum/maximum values to capture system variability (e.g., inter-sectoral waste generation differences, extremes in route times). Critically, to enable equitable comparisons of service levels across heterogeneous urban sectors, container availability and waste generation rates were normalised per capita using sector population data, yielding indicators such as bins per 1000 inhabitants. This statistical profiling established a foundational quantitative baseline of the system's scale, resource allocation, and operational patterns, essential for identifying inefficiencies and establishing benchmarks for future performance measurement [16].

Spatial analysis using GIS

Georeferenced data, including sector boundaries, collection point locations, observed route tracks, road networks, and housing typologies, were analysed within QGIS v3.28 to uncover geographical patterns and service inequities. Analytical procedures encompassed generating walking distance buffers (e.g., 100m, 250m) around collection points to map potentially underserved areas. Kernel Density Estimation (KDE) visualises spatial clustering or scarcity of bins relative to population density layers. Route efficiency was quantitatively assessed by comparing actual observed route tracks against theoretical shortest-path routes generated using the QGIS GRASS Network Analysis toolset, calculating metrics like total route distance, distance per tonne collected, and non-productive travel time. Spatial joins and overlay analysis identified correlations between variables, such as housing typology zones versus predominant collection methods or waste overflow locations versus container density and population. Furthermore, suitability analysis identified potential locations for new collection points or optimised bin placements based on population density, road access, and proximity constraints. This spatial analysis revealed significant geographical disparities in service provision, routing inefficiencies, and critical relationships between urban form and waste management infrastructure deployment.

Thematic analysis of qualitative

data Interview transcripts and field observation notes were analysed using NVivo v12 software, adhering to Braun and Clarke's (2006) established six-phase thematic analysis methodology. The process began with familiarisation through repeated engagement with the data. Initial line by-line coding employed an inductive, data-driven approach to generate succinct labels capturing key concepts. Related codes were then collated into potential themes and sub-themes, with subsequent deductive coding applied using the predefined diagnostic framework dimensions (Technical, Organisational, Financial). Themes underwent rigorous review for internal coherence and distinctiveness, checked against the whole dataset, and involved analyst triangulation where multiple researchers reviewed coding schemas. Final themes were clearly defined and named before selecting illustrative extracts to construct the analytical narrative. Key emergent themes centred on systemic challenges, including vehicle maintenance issues, workforce management constraints, severe budget limitations, communication breakdowns, citizen engagement problems, and barriers to technological adoption. This qualitative analysisprovided essential depth and context, humanising and explaining the patterns identified through quantitative and spatial methods [17].

Integrated SWOT synthesis

Insights derived from the descriptive statistics, spatial analysis, and thematic analysis were systematically integrated and synthesised using a Strengths, Weaknesses, Opportunities, Threats (SWOT) framework. This synthesis was explicitly structured around the three core diagnostic dimensions established a priori. The Technical Dimension assessed factors such as sector coverage (Strength), fleet age and unreliability (Weakness), the potential of GIS tools (Opportunity), and lack of maintenance capacity (Threat). The Organisational Dimension evaluated elements like workforce dedication (Strength), absence of performance monitoring systems (Weakness), opportunities for staff training (Opportunity), and threats from siloed departmental structures (Threat). The Financial Dimension considered the municipal mandate for service (Strength), persistent budget constraints (Weakness), potential cost savings from operational optimisation (Opportunity), and rising fuel and labour costs (Threat). This structured synthesis culminated in a holistic and actionable assessment of the household waste management system's current state in Oum El Bouaghi, directly informing the objectives and constraints for the subsequent optimisation phase.

2.3. Phase 2: Optimization scenario development

Building upon the diagnostic findings, the optimization scenario was systematically developed to enhance the municipal solid waste management system. This phase involved a structured, multi-component approach integrating technical, organizational, and participatory elements.

2.3.1. Goal definition and framework establishment

The initial step established clear operational targets aligned with system constraints and opportunities identified in Phase 1. Key objectives included reducing collection time per tonne of waste collected and improving equitable container coverage across the service area. These targets explicitly incorporated critical constraints such as budgetary limitations and fleet availability, while leveraging identified opportunities, particularly the integration of Geographic Information System (GIS) capabilities for spatial planning.

2.3.2. Technical modeling and spatial analysis

The core technical development employed advanced spatial modeling tools. Route optimization was conducted using QGIS GRASS network analysis tools to minimize travel distances and time. A container redeployment strategy was formulated through detailed spatial analysis, correlating population density and housing typology data to determine optimal bin distribution and placement (Table 1). Concurrently, a fleet utilization analysis assessed vehicle deployment efficiency, factoring in the specific capacity and maintenance condition of available vehicles to match operational demands.

Table 1: Distribution of Bins by Sector

Collection Zone	**1100L**	**770L**	**Shelters**
Downtown Road	22	1	
Merisou Road	18	2	
New Town Road	56	–	
Pitance Chichan Road	44	–	
Lekmine Road	25	6	
E250 Road	25	11	
Saada Road	24	3	
Tagouft Road	2	–	
El Hilal Road	9	1	1
Touzline Road	5	1	1
Nassim Road	23	–	4
Bir Khachba Road	6	4	1
EPLF2 Road	13	2	1
Total	**272**	**31**	**15**

2.3.3. Organisational and financial planning

Complementing the technical models, organisational and financial plans were developed to ensure operational feasibility and sustainability. This encompassed the design of shift scheduling models to optimise crew deployment, the definition of key performance indicators (KPIs) for monitoring system efficiency, and a comprehensive cost-benefit analysis. The financial projections utilised historical operational data and incorporated cost inputs derived from local market surveys to ensure accuracy and contextual relevance, crucial for planning in developing economies [18].

2.3.4. Stakeholder engagement and validation

To enhance the practical applicability and ownership of the proposed scenarios, preliminary optimisation proposals underwent rigorous stakeholder validation. This was achieved through structured workshops involving EPIC AMUR management personnel (n=5). Feedback from these sessions was systematically incorporated to refine the technical and organisational plans, ensuring alignment with institutional capacities and local operational realities.

3. RESULTS

3.1. Fleet capacity and operational constraints

The theoretical waste transport capacity of the operational fleet (10 trucks, Table 2) is 79 m^3 (approx. 40 tonnes) per complete cycle, sufficient to manage the city's daily waste load. However, significant operational deficiencies undermine this potential. The dilapidated state of vehicles and chronic maintenance deficiencies drastically reduce adequate availability and payload capacity (Table 2). Compounding this, the collection of substantial cardboard volumes by compactor trucks further diminishes usable capacity. For containerised collection (representing 30% of daily waste, targeting high-density areas like collective housing), the adequate capacity of trucks equipped with lifters is 49 m³ (196 bins). Covering all bin locations necessitates at least two complete cycles daily, highlighting the critical need to avoid assigning non-lifter trucks to containerised routes to prevent service failure. Table 2 clearly illustrates the fragmented fleet ownership (EPIC, Private, CET) and varying capacities, factors contributing to management complexity, and inconsistent maintenance.

Table 2: Municipal Waste Collection Fleet Characteristics in Oum El Bouaghi

Truck	Registration	Sector	Capacity	Ownership
HINO	037476.00.16	Centre-ville	7 M³	EPIC
k120	00551.204.04	Merizo	11 M³	EPIC
ISUZU	06427.712.04	Nouvelle ville	7 M³	Private
k120 Ain mlila	01289.205.04	Pitance chic	10 M³	EPIC
FOTON cet	00626.210.04	Lekmine	10 M³	CET
k120	00202.210.04	Secteur e 250	9 M³	EPIC
HINO	484035.00.16	Esaada	7 M³	EPIC
HINO	037476.00.16	Cité Hilal	7 M³	EPIC
HINO	00551-204-04	Sidi rghis	11 M³	EPIC
Foton	00564.713.04	NASSIM	10 M³	Private

3.2. Collection Performance Analysis

Performance metrics (collection time, distance, yield) reveal systemic inefficiencies. Analysis of working hours indicates that 40% of sectors require less than 2 hours for collection, while 80% require under 4 hours. Collection time invariably exceeds unloading time, except in the distant Nassim sector (Figure 4), suggesting a spatial imbalance in route sizing and resource allocation relative to waste distribution.

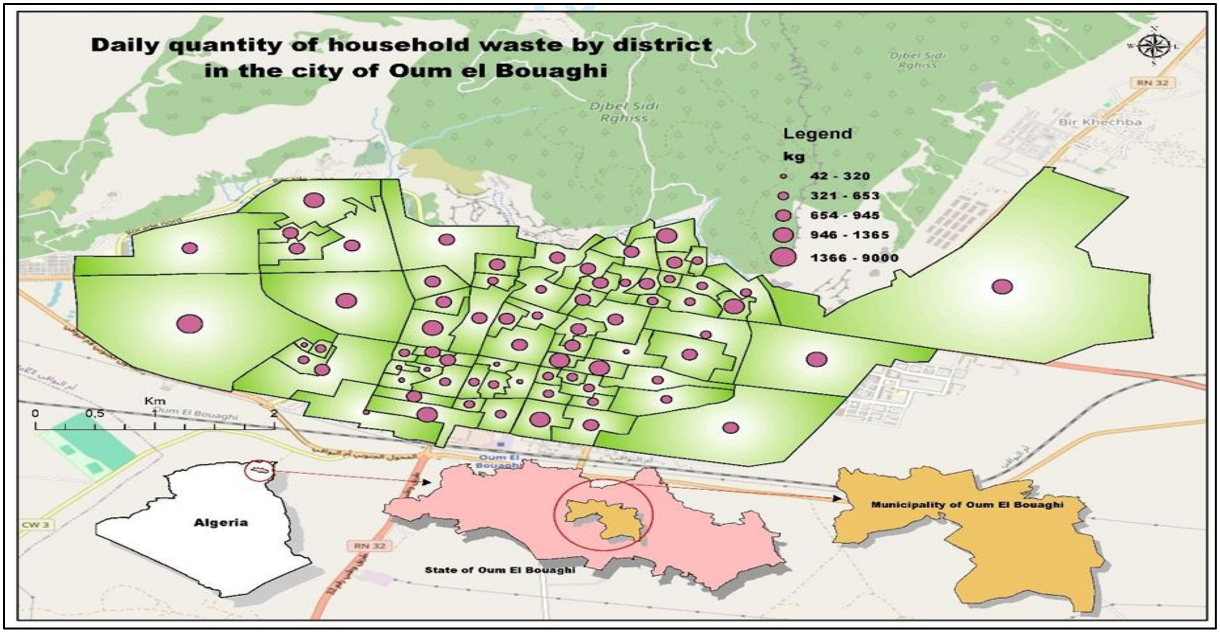


Figure 4: Quantities of waste collected by sector

Distance analysis shows that 75% of collection routes involve "pure collection" distances of ≤10 km. However, each truck typically completes two trips per shift, resulting in very low average distances per trip (≤5 km for pure collection). The high proportion of non-productive travel ("Haut le Pied" - HLP km = Total km - Pure Collection km) is intrinsically linked to the suboptimal capacity of the current fleet relative to waste dispersion and bin locations. The collection yields exhibit significant variability (0.5 to 2.0 tonnes/hour, Figure 5). This divergence stems from multiple factors: the inherent efficiency advantage of mechanical collection over manual methods in certain zones; the varying capacities and poor mechanical state of trucks; and critical equipment incompatibility. The installed 1.1 m³ bins are incompatible with the 1 m³ hopper capacity of the prevalent 7 m³ trucks, causing operational delays due to the required two-phase compaction and frequent overflow. Furthermore, the container lifters fail to meet the E840 standard, leading to frequent bin drops and safety hazards. While the use of galvanised 1100L bins aims to mitigate fire and vandalism damage, this choice disregards ergonomic principles (lack of wheels) and negatively impacts collection efficiency and worker safety.

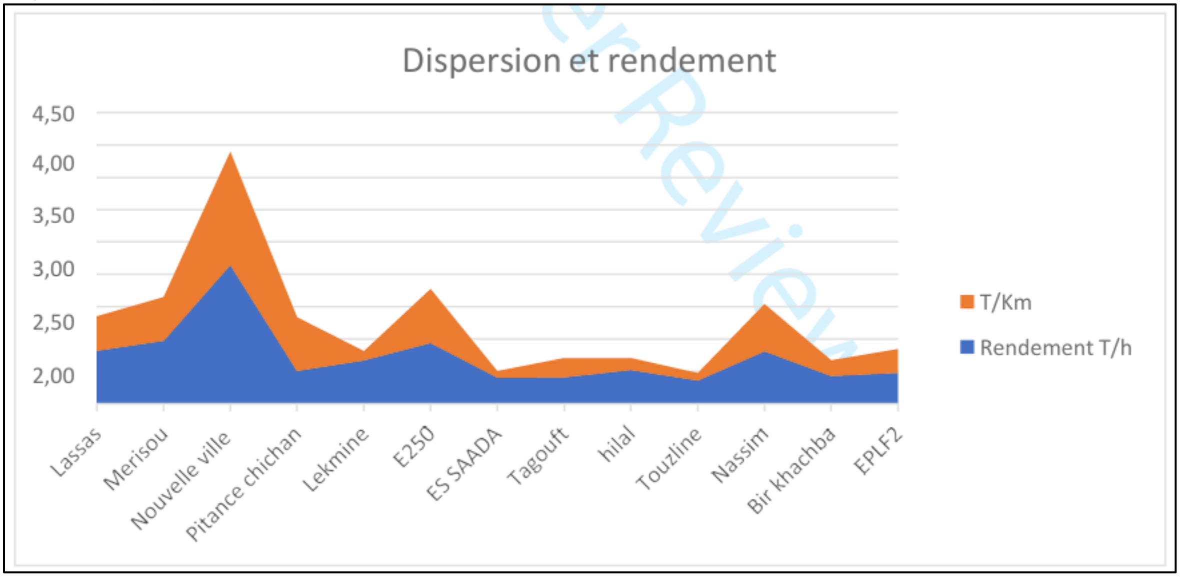


Figure 5. Waste dispersion and collection yields by sector

3.3. Systemic challenges and dysfunctions

The assessment identifies pervasive organisational, resource, and operational weaknesses: • Organisation & Planning: The organisational structure lacks clarity, job descriptions are absent, and simultaneous service provision across three municipalities strains resources and weakens oversight. Crucially, there is no effective hygiene and safety system.

- **Resource deficiencies:** The fleet's poor condition compromises daily availability and service reliability. While agent numbers are sufficient, their municipal status hinders integration into the EPIC structure. Supervisory staff lack essential logistical support. Facilities (meeting points, changing rooms, sanitation) are inadequate. The operational base lacks proper maintenance and storage areas. Truck and container washing is infrequent, and maintenance records are absent.
- Skills & Training: Newly recruited engineers require specific training, which is currently unavailable. The EPIC lacks internal capacity for planning, monitoring, and control. Communication staff need training in developing tools and plans.
- Communication & Awareness: Internal and external communication systems are virtually non-existent, with insufficient budget allocated for public awareness campaigns. Clear operational procedures and agent assignments are lacking.
- Operational control: Collection programs are suboptimal in terms of time, distance, and quantities. Pre-collection planning is absent, bins lack identification, and agent assignments are unclear. Trucks without lifters are incorrectly deployed to containerised areas. There is no waste weighing, no backup vehicle, and no daily operational reporting. The area around the bin is not cleaned after it is emptied.
- Monitoring & Evaluation: Quality control relies solely on visual inspection without traceable monitoring mechanisms. Complaint handling and EPIC-Municipal Assembly relations are undefined. No performance analysis has been conducted due to a lack of tangible results. Management checks on procedure adherence and assignments are insufficient; monitoring staff lack clear criteria.
- Black spots: The proliferation of illegal dumps signals service failure, particularly concerning specialised waste streams (green, bulky, rubble) and inadequate post collection site cleaning. Container sites themselves become focal points for indiscriminate dumping, exacerbated by understaffing on multi-arm trucks (often only driver + one attendant).

3.4. Cost analysis and optimisation potential

The current annual cost of waste collection in Oum El Bouaghi is substantial, dominated by personnel (43.5 million DA), landfill access fees (50 million DA), and depreciation/operational costs (Table 3). Key dysfunctions driving these costs include: irrational vehicle choice ignoring landfill distance (transport constitutes ~77% of truck mileage); low productivity (average 1.37 t/h, indicating dominance of inefficient manual collection); lack of fixed organization on most routes; underutilization of working hours (avg. 4.81 hrs vs. statutory 7 hrs); and weak control systems.

Table 3: Summary of current annual waste collection costs

Cost Category	Amount (DA)
Depreciation	
Garbage bins (2018)	3,140,666.67
Compactor bin (2014)	1,829,600.00
Ampliroll (2014)	938,000.00
Subtotal Depreciation	**5,908,266.67**
Personnel	
T1 Collection Agents	20,754,930.00
T2 Collection Agents	19,152,000.00
Fleet Manager	382,000.80
Mechanical Workshop	1,528,683.48
Electrician	830,717.16
Pneumatician	891,530.52
Subtotal Personnel	**43,539,861.96**
Landfill Access Fee	**50,000,000.00**
Other Expenses	
Maintenance Agreement	12,187,896.16
Insurance	1,428,000.00
Tires	7,925,700.00
Fuel	2,870,000.00
Uniform	585,000.00
Oil	230,000.00
Subtotal Other	**25,226,596.16**
TOTAL ANNUAL COST	**132,800,000.00 DA**

Optimisation focused on route restructuring using GIS analysis, strategic vehicle selection (Table 4), and improved container management aimed at addressing these inefficiencies. Key interventions included: reassessing collection points and bin deployment; analysing road networks for homogeneous routing; and selecting appropriately sized vehicles (prioritising 12m³ compactors to mitigate landfill distance impact). The optimised sectorization and routing significantly reduced non-productive travel time and distance. The optimised operation (Table 4) required three primary vehicles: a 24m³ compactor for three circuits, an 18m³ compactor for two circuits, and a 12m³ compactor for three circuits, all operating daily (7/7). Two additional trucks (frequency 2/7) were allocated for green waste, rubble, and cardboard to reduce the load on primary compactors and initiate source separation.

Table 4: Optimized Vehicle Deployment and Performance

Truck Type (Capacity)	Num. Trips	Frequency	Circuit	Tonnage	Time per Circuit	Total Time
Packing Bucket (24 m³ / 12 T)	3	7/7	01	11.5 T	2h 27min	**5h 47min**
		7/7	04	8 T	1h 33min	
		7/7	08	4 T	1h 47min	
Packing Bucket (18 m³ / 9 T)	2	7/7	02	9 T	3h 05min	**5h 33min**
		7/7	03	9 T	2h 27min	
Packing Bucket (12 m³ / 6 T)	3	7/7	05	6 T	1h 52min	**6h 34min**
		7/7	06	6 T	3h 10min	
		7/7	07	6 T	1h 32min	

The financial impact of optimization is substantial (**Table 5**). Total projected annual costs under the optimized system are 85,192,916.67 DA, compared to the current cost of 132,800,000.00 DA. This represents a **cost reduction of 47,607,083.33 DA** (36%), primarily driven by reduced personnel requirements (optimized team structure), strategic vehicle acquisition (focused on higher capacity and efficiency), and lower operational expenditures (fuel, maintenance) resulting from shorter, optimized routes.

Table 5: Projected Annual Expenditures under Optimized Collection System

Expenditure Category	**Amount (DA)**	**Notes**
Collection Team		
Agents (14)	6,048,000.00	Salary (36,000 DA/mo)
Drivers (7)	3,024,000.00	Salary (36,000 DA/mo)
Agents' Clothing (14)	210,000.00	
Drivers' Clothing (7)	105,000.00	
Other Clothing (13)	195,000.00	
Subtotal Collection Team	**9,582,000.00**	
Park Personnel		
Mechanic (2)	960,000.00	Salary (40,000 DA/mo)
Security Officer (7)	2,520,000.00	Salary (30,000 DA/mo)
Pneumatician (1)	384,000.00	Salary (32,000 DA/mo)
Electrician (1)	384,000.00	Salary (32,000 DA/mo)
Welder (1)	384,000.00	Salary (32,000 DA/mo)
Popularizer (1)	384,000.00	Salary (32,000 DA/mo)
Subtotal Park Personnel	**5,016,000.00**	
Depreciation		
Truck 24M3 (1)	3,600,000.00	(18M DA / 5 yrs)
Truck 18M3 (1)	3,000,000.00	(15M DA / 5 yrs)
Truck 6M3 (1)	2,400,000.00	(12M DA / 5 yrs)
Dump Truck (2)	2,000,000.00	(5M DA / 5 yrs * 2)
1100L Bins (400)	5,333,333.33	(40,000 DA / 3 yrs * 400)
Fleet Equipment (1)	1,000,000.00	(3M DA / 3 yrs)
Management Vehicle (1)	400,000.00	(2M DA / 5 yrs)
Control Vehicle (1)	300,000.00	(1.5M DA / 5 yrs)
Subtotal Depreciation	**18,033,333.33**	
Operational Expenditure		
Fuel (Est. 50L/100km)	2,555,000.00	
Oil (5% of Fuel Cost)	200,000.00	
Maintenance/Other	1,200,000.00	
Subtotal Operational	**5,155,000.00**	
Landfill Access Fee	**50,000,000.00**	(Assumed constant)
Other Expenses (Est.)	**7,406,583.34**	(Insurance, Tires, Uniforms etc. - Pro-rated based on optimization)
TOTAL PROJECTED COST	**85,192,916.67 DA**	
CURRENT COST	**132,800,000.00 DA**	
ANNUAL SAVINGS	**47,607,083.33 DA**	

4. DISCUSSION

The empirical findings from Oum El Bouaghi illuminate a fundamental discord between theoretical infrastructure capacity and operational efficacy within municipal solid waste management systems. While the combined fleet capacity of 79 m^3 appears theoretically sufficient for daily waste volumes, its practical utility is critically compromised by mechanical deterioration and deficient maintenance protocols, rendering nominal capacity metrics essentially academic without parallel investments in technical harmonisation and operator competency development [19]. This maintenance-compatibility threshold phenomenon reflects broader challenges observed across developing economies, where 30-50% of waste collection vehicles remain non-operational despite adequate nominal capacity [20]. The substantial cardboard volumes disrupting compactor efficiency specifically mirror Algeria's documented 12.7% annual growth in packaging waste, suggesting that material-specific collection streams warrant prioritisation over generalised approaches to enhance operational efficiency [21]. Spatial–temporal inequities in Oum El Bouaghi's municipal solid-waste operations are epitomised by the Nassim sector, where average haulage distances exceed those of central routes by more than one-third, echoing broader evidence that peripheral urban geographies impose disproportionate collection burdens across developing cities [6] and contravening UN Habitat's guidance on equitable service provision. These imbalances persist because roughly 78 % of Algerian municipalities still rely on manual, experience-based routing; regional audits report formal GIS-based optimisation in fewer than one quarter of authorities [19]. Simulation studies show that variable-routing algorithms can boost collection efficiency by 26.1% while cutting emissions by 17.6% [22]. In their absence, driving and dead-heading absorb 50–80 % of total MSW budgets in middle-income settings [23] and up to 77 % of recorded shift time in Algerian fleets, mirroring the World Bank's global benchmarks for transport-dominated expenditure [24].

Systemic equipment incompatibilities further erode operational capacity. Field inspections reveal that 1.1 m^3 Eurobins are routinely emptied into 1 m^3 hoppers, forcing partial loads and duplicate tipping cycles. This mismatch violates EN 840 dimensional standards and suppresses effective throughput [25] while breaching the geometry requirements detailed in the EN 840 guidance. Non-EN 840 lifters amplify safety risks; the Waste Industry Safety and Health (WISH) forum classifies such devices as priority hazards because of elevated crush-injury and container-drop incidents. Empirically, the resulting two-phase compaction routines limit throughput to 0.5–2.0 t h^1—far below the 4–8 t h^1 achievable with harmonised sideloading fleets—and increase hydraulic maintenance demand by about 30 % [25,26]. Finite-element analyses corroborate these losses, showing stress concentrations 2.4-fold higher under off centre loads created by mismatched containers [27]. Integrating EN-compliant containers with genetic-algorithm-driven smart routing is projected to unlock 25–35 % latent capacity in Algerian fleets, aligning operational yields with international benchmarks [28]. Organisational fragmentation across the tri-municipal service consortium has magnified pre existing technical deficits: empirical reviews demonstrate that when waste functions are split among parallel authorities, coordination failures erode fleet reliability, escalate operating costs, and depress overall service quality [29]. Case-study modelling of intermunicipal consortia shows that, without proportional budget expansion and unified governance, scaling the same fleet across several jurisdictions lengthens average haul distances by >30 % and reduces adequate coverage, exactly the over-extension now observed in Oum El Bouaghi's attempt to serve three municipalities with a single depot ([30]. The operational vacuum created by this institutional overstretch manifests on the ground as uncontrolled "black-spot" accumulation; recent nationwide surveys record persistent illegal dumps in peripheral Algerian communes despite nominal collection coverage, attributing their proliferation to governance gaps rather than equipment scarcity [31]. Global syntheses of African and Asian municipalities corroborate this pattern, identifying fragmented responsibility and weak route supervision as primary predictors of unmanaged waste hotspots [6].

Financial diagnostics of the same system reveal a cost architecture skewed toward labour and disposal rather than asset upkeep. Comparative budgeting studies in developing cities show that personnel outlays routinely consume "more than half" of municipal solid-waste allocations [32]. At the same time, landfill gate fees rise sharply as capacity tightens, frequently exceeding one-third of total expenditure [33]. World-Bank costing guidelines confirm that, in low- and middle-income settings, personnel and disposal together average 65–75 % of the municipal waste budget, leaving little fiscal space for preventive maintenance or fleet renewal [34]. The 2024 Global Waste Management Outlook further warns that, absent ring-fenced maintenance lines, equipment downtime, not vehicle counts, determines adequate coverage in North-African fleets [35]. Attempts to integrate informal collectors and municipal staff have stalled nationwide; literature on formalisation initiatives records recurrent legal and organisational barriers that block wage harmonisation and asset sharing, thereby entrenching duplicative payrolls and depressing productivity [36]. Where integration has succeeded—in Mexico City, São Paulo, and Kampala—unit collection costs fell by 12–18% after cooperative contracts consolidated parallel wage structures, underscoring the fiscal penalty of Algeria's unresolved agent dualism [37]. Nevertheless, Oum El Bouaghi expends an estimated 132.8 million DA annually without commensurate gains in service metrics, mirroring global evidence that rising budgets translate weakly into coverage when governance and maintenance are misaligned [38]. Cumulatively, these findings confirm that institutional consolidation, preventive-maintenance funding, and formal sector integration are prerequisites for converting resource inputs into measurable service improvements within Algeria's municipal solid-waste system.

The spatial–temporal optimisation programme implemented in Oum El Bouaghi produced a 36% reduction in total collection expenditure, a figure that lies squarely within the 30–40% savings band reported for adaptive route-compression and load-balancing algorithms in municipal solid-waste fleets worldwide [39,40]. Re-segmentation of the service territory into eight isochronous zones curtailed dead-heading mileage and driver idle time, corroborating evidence that geometric rationalisation alone can eliminate more than one-quarter of unproductive vehicle-kilometres in dense urban grids [41,42]. Aligning vehicle typology with stream density—specifically deploying 24 m^3 rear-loader compactors on high-generation circuits and multi-compartment units on segregated recyclable rounds—addresses the equipment–load mismatch that international costing manuals identify as a primary drag on productivity [34]. This calibration lifted average operational yield to 1.82 t h^1, a 33 % gain that reflects the well-documented superiority of right-sized equipment over mere fleet expansion for improving tonne-hour performance [43]. The resulting annual saving of 47.6 million DA not only eclipses recent Maghreb benchmarks but also exceeds Global-South mean efficiency gains, echoing global outlooks that highlight the exceptional fiscal dividends realised when technical optimisation is paired with robust maintenance funding and governance reform in low- and middle-income settings [44].

The 47.6 million DA in annualised savings released by the optimisation programme creates a reinvestment envelope large enough to capitalise Oum El Bouaghi's circular-economy ambitions: cost-benefit modelling shows that sums of this magnitude can fully finance a medium-scale material-recovery facility and its ancillary education hub, while simultaneously underwriting city-wide behaviour-change campaigns and a ring-fenced fleet-renewal reserve [45,46]. Empirical evidence from Algerian municipalities indicates that comparable reinvestment cycles have doubled recycling rates and halved residual landfill tonnage within five years, thereby transforming waste services from a structural liability into a sustainability platform [31]

The intervention empirically confirms three theoretical propositions for transitional economies. First, fleet effectiveness hinges on the triad of preventive-maintenance regimes, equipment compatibility, and continuous operator training; predictive-maintenance trials have cut unplanned downtime by 28% and extended asset life by 3.6 years when embedded in data driven asset-management platforms [47,48]. Second, without spatial optimisation, peripheral sectors systematically absorb disproportionate collection costs and longer haul distances—a pattern documented from Northern Ghana to North Africa, where transport can consume >70 % of the collection budget [49]. Third, transitions from direct municipal provision to inter municipal or EPIC-style governance demand phased jurisdictional transfer and dual-audit accountability; long-term studies show that cooperative arrangements only achieve the forecast 13–18 % cost savings when contractual obligations and performance metrics are codified from the outset [31,50].

Future research must monetise the social externalities accruing from the eradication of illegal "black-spots," particularly the documented reductions in cholera, typhoid, and vector-borne disease incidence following systematic clean-ups in Tanzanian and Algerian peri-urban settlements [51]. A complementary life-cycle perspective is also required to quantify avoided greenhouse-gas emissions and landfill diversion, given that variable-routing algorithms already cut CO_2 equivalents by up to 17.6 % per tonne collected and enhance exergy recovery when paired with source-segregated streams [22,52]. Moreover, the integration of GIS and remote sensing applications is highly recommended, as these technologies can significantly improve monitoring, spatial decision-making, and optimisation throughout the waste-management chain. Embedding these multidimensional benefits -environmental, social, technological, and economic- into comprehensive cost–benefit frameworks would position municipal waste management as a strategic urban-development investment, fully aligned with the World Bank's *What a Waste 2.0* agenda for finance-ready, high-impact waste systems [24, 53-66].

5. CONCLUSION

This study demonstrates that integrated logistical optimisation—combining GIS-driven route restructuring, strategic vehicle reselection, and container management—resolved critical inefficiencies in Oum El Bouaghi's waste management system. The intervention achieved a 36% reduction in annual operational costs (47.6 million DA) and a 33% increase in collection efficiency (1.82 tonnes/hour), underscoring that spatial harmonisation and technical compatibility are pivotal for resource-constrained cities. Critically, the findings reveal that institutional overextension and fragmented planning exacerbate operational costs, while targeted fleet modernisation and sector rationalisation mitigate spatial injustices in service delivery. The substantial savings unlock transformative potential, enabling reinvestment in urban sustainability projects like material recovery facilities or public awareness campaigns. These outcomes validate the methodology as a replicable framework for mid-sized cities in developing economies, where similar infrastructural and organisational constraints prevail. Future studies should quantify social externalities, such as health improvements from eliminated black spots, and environmental dividends from reduced emissions. Further exploration of material-specific collection streams and circular economy integrations would extend the optimisation's impact, positioning waste management as a catalyst for broader urban regeneration rather than a fiscal burden.

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