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Towards Smart Urban Waste Collection in Sub-Saharan Africa: An IoT-Based Framework for Mombasa County, Kenya

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Abstract: *Urban solid waste management has emerged as a major environmental and logistical challenge in rapidly urbanizing coastal cities of Sub-Saharan Africa. Existing waste collection practices based on static schedules and manual supervision are increasingly unable to cope with rising waste generation, resulting in bin overflow, environmental degradation, and public health risks. This study investigates the feasibility of, and identifies key design requirements for, an IoT-based waste collection framework to optimize waste collection processes in Mombasa County, Kenya. Mombasa City, a developing coastal urban centre, has approximately 1.3–1.6 million residents and generates an estimated 2,200 tonnes of solid waste daily. A quantitative descriptive research approach was adopted using structured questionnaires administered to 220 purposively selected respondents: 120 residents and 100 technical staff from three geographic zones. Findings reveal challenges: 68.3% of residents experience regular or frequent bin overflows, while 62.5% receive collection fewer than twice per week. Additionally, 53% of organizations lack formal waste management systems, 67% lack real-time monitoring, and 70% of technical staff are unprepared or uncertain about IoT readiness. The study proposes an IoT architecture integrating ultrasonic sensors, GPS tracking, LoRaWAN or NB-IoT communication, and A* route optimization supported by a hybrid edge–cloud platform, offering a replicable model for East African urban contexts.*

Keywords: *Internet of Things (IoT); Smart Waste Management; Urban Solid Waste Collection; Route Optimization; Smart Cities; Mombasa County; Sub-Saharan Africa.*

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1. Introduction

Waste management remains a major environmental and urban governance challenge in rapidly urbanizing cities across the Global South. The volume of municipal solid waste (MSW) generated worldwide is projected to reach 3.4 billion tonnes annually by 2050, with low- and middle-income countries absorbing the largest incremental burden (Wilson et al., 2022). In Sub-Saharan Africa, the combination of rapid population growth, informal urbanization, and constrained public budgets creates a structural mismatch between waste generation rates and collection capacity (Ferronato & Torretta, 2019; Zohoori & Ghani, 2017).

Mombasa County, Kenya, exemplifies these challenges. As a coastal urban centre and major hub for trade and tourism, the county hosts an estimated 1.3–1.6 million inhabitants and generates approximately 2,200 tonnes of solid waste per day, of which only 60–65% is formally collected (Gakungu et al., 2021; Wekisa & Majale, 2020). The uncollected waste is frequently discarded in informal dumping areas, drainage networks, and public spaces, generating cascading consequences for public health, the tourism economy, and the coastal marine environment (Otundo Richard, 2016). Current waste collection systems rely primarily on fixed schedules, manual route planning, and paper-based documentation, which may constrain their ability to adapt to changing waste generation patterns and to manage a dynamic and

spatially heterogeneous waste stream (Oche Idoko et al., 2024).

Globally, the Internet of Things (IoT) has become a key enabling technology for enhancing the efficiency and sustainability of smart waste management systems. Sensor-equipped bins transmit real-time fill-level data to cloud platforms, enabling demand-responsive collection, optimized routing, and evidence-based resource allocation (Ali et al., 2020; Arthur et al., 2024; Rai et al., 2025). Quantitative gains reported in the literature include 20–40% reductions in vehicle travel distance and 15–30% reductions in operational costs (Anagnostopoulos et al., 2015; Fang et al., 2015). Despite this global evidence base, the adoption of IoT-enabled waste management solutions remains limited across many secondary cities in East Africa, where infrastructure limitations, governance fragmentation, and low stakeholder readiness create distinctive implementation barriers (Siwawa, 2025).

1.1 Statement of the Problem

Despite the scale of Mombasa County's waste management challenge, the county's collection system continues to rely on fixed schedules, manual route planning, and paper-based documentation rather than on real-time information about bin fill levels or waste generation patterns. This mismatch between static, non-responsive collection practices and a dynamic, spatially heterogeneous waste stream results in frequent bin overflows, environmental degradation, and public health risks, and it is compounded by fragmented institutional capacity and uncertain stakeholder readiness for technological change. While IoT-based smart waste management has demonstrated measurable operational gains in other contexts, no empirically grounded IoT framework tailored to Mombasa's specific institutional, infrastructural, and stakeholder context currently exists. Therefore, the problem addressed by this study is the absence of an evidence-based, context-appropriate IoT framework capable of transforming Mombasa County's waste collection system from a static, reactive model into a dynamic, demand-responsive one.

This study addresses the resulting research gap by investigating the feasibility, perceived challenges, and design requirements of an IoT-based waste collection framework for Mombasa County. Three research objectives guide the work:

1) to review existing approaches and identify structural weaknesses in Mombasa's current waste collection system;
2) to assess the current challenges and stakeholder perceptions of the system's performance;
3) to develop an IoT-based framework capable of detecting real-time bin fill levels and optimizing collection routes, informed by local contextual constraints.

2. Literature Review

2.1 IoT Sensing and Smart-Bin Technologies

Smart waste bins are established IoT applications for urban waste management. They use ultrasonic sensors, RFID modules, gas and temperature sensors, and low-power microcontrollers such as ESP32 or Arduino for real-time monitoring (Singh, 2018). Data are transmitted via LoRaWAN or NB-IoT to cloud platforms for analytics and monitoring (Laha et al., 2023). These technologies support dynamic collection scheduling and route optimization, reducing fuel consumption and vehicle travel by 20–40% (Arthur et al., 2024; Rai et al., 2025).

2.2 Route Optimization and Decision Analytics

Route optimization converts real-time bin data into efficient collection schedules. Algorithms such as Dijkstra, Floyd–Warshall, and A*, together with Random Forest and ARIMA models, optimize routes and predict fill levels to prevent overflow (Jerbi et al., 2025). The A* algorithm is well suited to dynamic urban environments because it incorporates traffic conditions and bin priority. African pilot studies report operational benefits but identify infrastructure limitations and low stakeholder awareness as major implementation barriers (Wilson et al., 2022).

2.3 Theoretical Framework

The study is underpinned by Systems Theory, the Technology Acceptance Model (TAM), and Smart City Theory. Systems Theory explains waste management as an interconnected system enhanced by IoT (Bertalanffy, 1968; Zurbrügg et al., 2012). TAM explains technology adoption through perceived usefulness and ease of use (Davis, 1989). Smart City Theory positions IoT-enabled waste management within broader urban digital transformation (Albino et al., 2015; Nam & Pardo, 2011).

2.4 Research Gap

Although IoT has improved waste management globally, research in Sub-Saharan Africa focuses mainly on major cities. Secondary coastal cities such as Mombasa remain underexplored, and no published study has examined IoT deployment in this context. Existing studies also address fill-level monitoring and route optimization separately rather than as an integrated framework adapted to local conditions. This study addresses these gaps.

3. Methodology

3.1 Research Design

The study adopted a quantitative descriptive research design, utilizing structured questionnaire surveys for data collection administered to two distinct respondent groups. The study was conducted in Mombasa County, Kenya, across three geographic zones: the urban centre, residential estates, and peri-urban areas. Data collection was carried out in April 2026.

3.2 Sampling and Participants

Purposive sampling was employed to recruit 220 respondents, consisting of 120 residents and 100 technical staff members. The study involved two purposively selected respondent groups: residents representing end users, and technical personnel representing institutional stakeholders. This comprised 120 residents serving as end-user informants and 100 technical and ICT staff from the environmental and solid waste management departments of Mombasa County, for a total study sample of n = 220.

Table 1. Sample Composition by Stakeholder Category

Category	Target Population	Sample Size	% of Sample
Urban households	400,000	120	54.5
Formal waste service providers	50	30	13.6
Informal waste collectors	200	25	11.4
Government officials	30	20	9.1
Community-based Organisations	20	25	11.4
TOTAL	**400,300**	**220**	**100**

3.3 Data Collection Instruments

Two structured questionnaires were pilot-tested with eight participants to evaluate their clarity, relevance, and reliability prior to the main data collection. The resident questionnaire covered collection frequency, bin fill and overflow experience, perceived challenges, efficiency ratings, attitudes toward smart waste management, and willingness to pay. The technical staff questionnaire addressed formal management systems, monitoring capabilities, system effectiveness and limitations, IoT awareness and adoption readiness, and priority recommendations. Both instruments were administered in English and Swahili.

3.4 Proposed IoT System Architecture

The proposed framework integrates four layers: (1) a perception layer comprising smart bins equipped with HC-SR04 ultrasonic sensors, DHT22 temperature and humidity sensors, gas detection sensors, RFID modules, and ESP32 microcontrollers for real-time waste monitoring; (2) a communication layer using LoRaWAN or NB-IoT with the MQTT protocol; (3) a processing layer built on a hybrid edge–cloud platform (Node.js server, MySQL time-series database); and (4) an application layer providing a real-time dashboard, overflow alerts at 80% capacity, predictive fill-level forecasting (Random Forest, ARIMA), and A* route optimization. Figure 8 presents the system architecture schematic.

3.5 Data Analysis

Quantitative data were analyzed using descriptive statistics and cross-tabulation. Cross-group comparative analysis between resident and technical staff survey responses was conducted to identify convergences, divergences, and perceptual differences across five analytical dimensions. All statistical analyses were conducted in SPSS v28.

3.6 Ethical Considerations

Ethical clearance for the study was obtained from the Institutional Ethics Review Committee of Moi University prior to data collection. Participation was entirely voluntary, and informed consent was obtained from all respondents before questionnaire administration. Respondents were assured of the confidentiality and anonymity of their responses, and no personally identifiable information was collected or retained. Data were used strictly for academic purposes, stored securely, and made accessible only to the research team.

4. Results and Discussion

4.1 Waste Collection Frequency (Residents)

Figure 1 presents the distribution of waste collection frequencies reported by residents. Only 15.8% of residents reported receiving daily waste collection

services, with these services predominantly concentrated in well-resourced central urban areas. Overall, 62.5% of residents reported that waste collection services were provided fewer than twice per week, including 23.3% who described collection as irregular and 19.2% as rare. This finding may account for the high prevalence of waste bin overflows reported in Section 4.2.

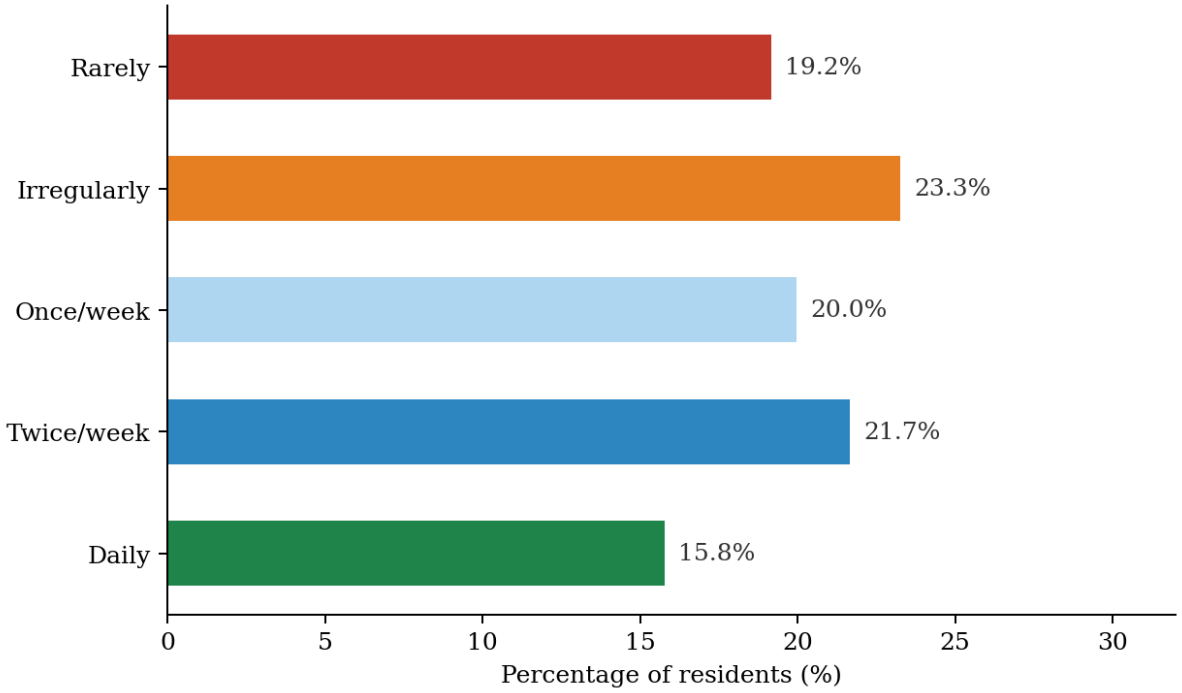


Figure 1. Waste Collection Frequency Reported by Residents (n = 120)

4.2 Bin Fill Status and Overflow Experience

Figure 2 presents bin fill status and overflow experience data. None of the residents reported encountering empty or moderately filled waste bins. Instead, all respondents (100%) indicated that waste bins frequently reached problematic fill levels (sometimes full: 36.7%; often full: 32.5%; always full: 30.8%). Regarding overflow frequency, 36.7% experience it frequently, 31.7% occasionally, and 31.7% rarely. Overall, 68.3% of residents reported experiencing regular or frequent waste bin overflows, constituting both a sanitary emergency and the primary rationale for deploying real-time IoT fill-level monitoring.

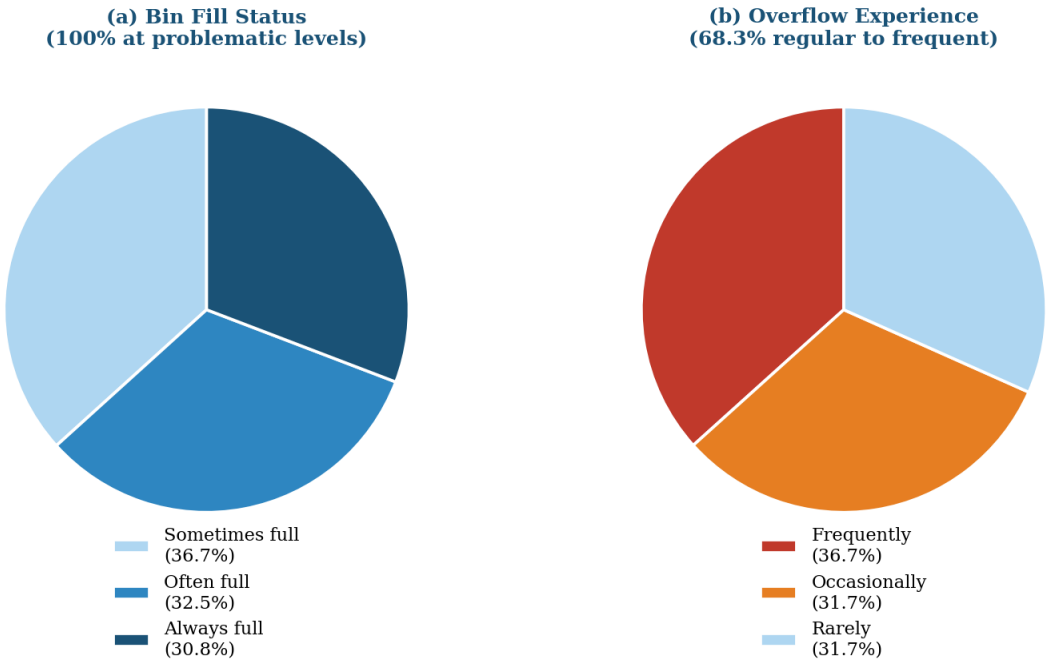


Figure 2. Bin Fill Status (left) and Overflow Experience (right) Residents (n = 120)

4.3 Observed Challenges: Triangulation

Figure 3 provides a comparative view of challenges identified by both groups, enabling inter-group triangulation. Bad odour is the most cited challenge by both residents (36.7%) and technical staff (30%), confirming a systemic sanitary problem. Delayed collection is confirmed by 31.7% of residents and 23% of technical staff. Traffic disruption was reported by 31.7% of residents but was not identified by technical staff, indicating a divergence in stakeholder perceptions with direct implications for route optimization design. Bin shortages (26%) and community compliance issues (21%) are identified by technical staff only.

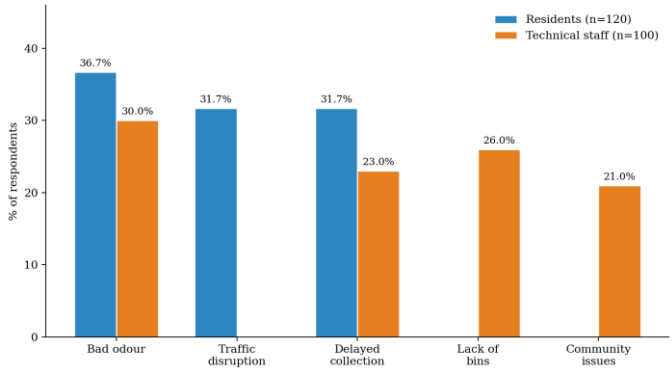


Figure 3. Triangulation of Observed Challenges: Residents vs. Technical Staff

4.4 System Efficiency Rating

Figure 4 presents efficiency ratings from both groups. Among residents, 63.3% rate the system as Fair or Poor; not a single resident awarded an Excellent rating. Technical staff also expressed similarly negative assessments: 57% rate the system they manage as Fair or Poor, indicating substantial concerns regarding institutional performance. The near-uniform distribution across categories among technical staff reflects significant performance heterogeneity across departments and geographic zones.

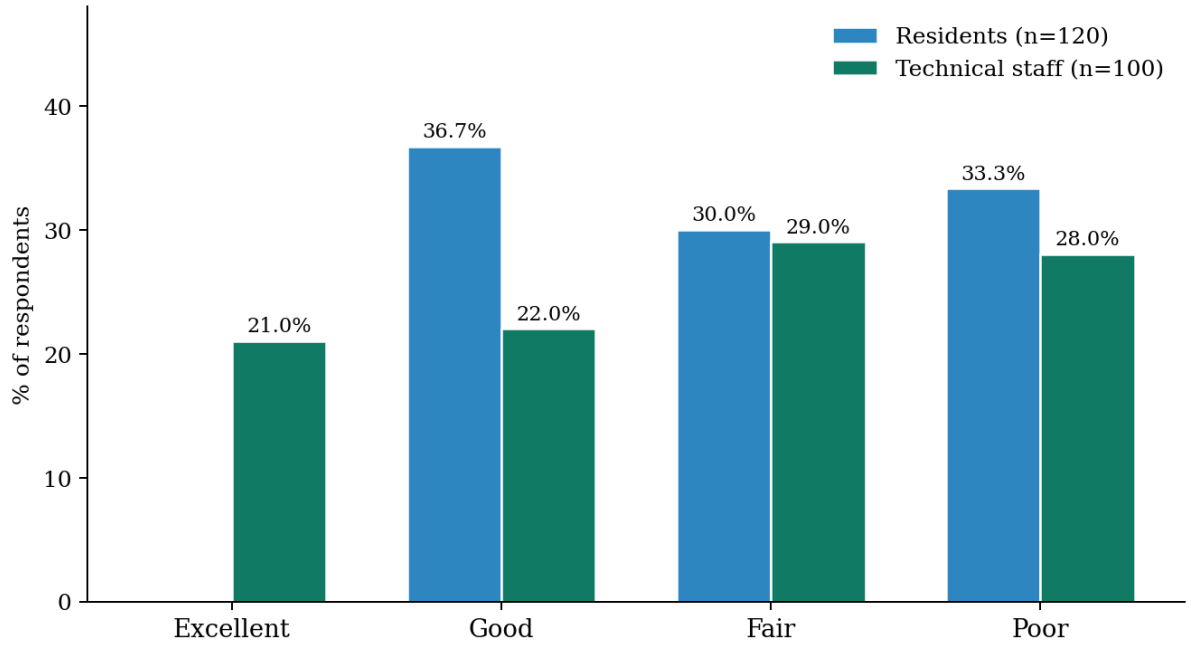


Figure 4. Efficiency Rating of the Current Waste Collection System — Both Groups

4.5 Formal Management Systems and Real-Time Monitoring

Figure 5 reveals the fragmented institutional landscape. Among the 47% of organizations that possess a formal system, four typologies coexist: integrated smart system (28%), fully digital (26%), manual/paper-based (24%), and semi-digital Excel-based (22%), highlighting differences in digital maturity levels that need to be addressed prior to large-scale IoT implementation. Regarding real-time monitoring, 37% of organizations have none, 30% have partial capability only, and just 33% have full real-time monitoring. In total, 67% operate without complete real-time visibility, constraining efficient real-time resource allocation.

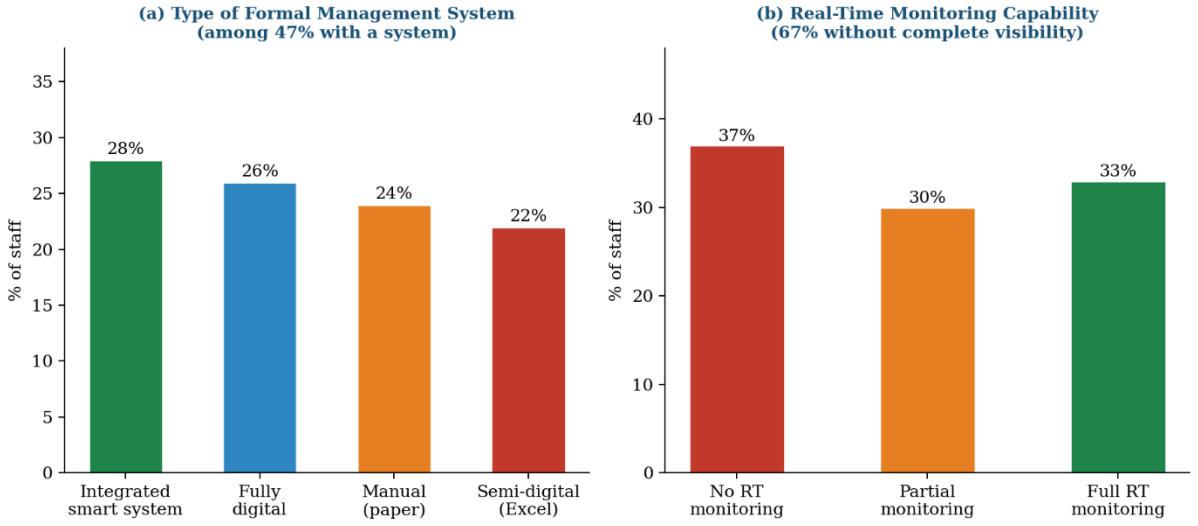


Figure 5. Formal Management System Types (left) and Real-Time Monitoring Capability (right), Technical Staff (n = 100)

4.6 IoT Adoption Readiness

Figure 6 presents the three dimensions of IoT adoption readiness. Regarding perceived benefits, only 44% of technical staff express a clearly positive perception, while 31% are uncertain and 25% negative. Support for adoption shows a near-equal three-way split: 36% in favour, 34% undecided, and 30% opposed, indicating a lack of institutional consensus. Importantly, only 30% consider their organization technically ready for IoT

deployment; 39% do not, and 31% are unsure. With 70% of staff either unprepared or uncertain, this constitutes one of the key operational constraints identified in this study.

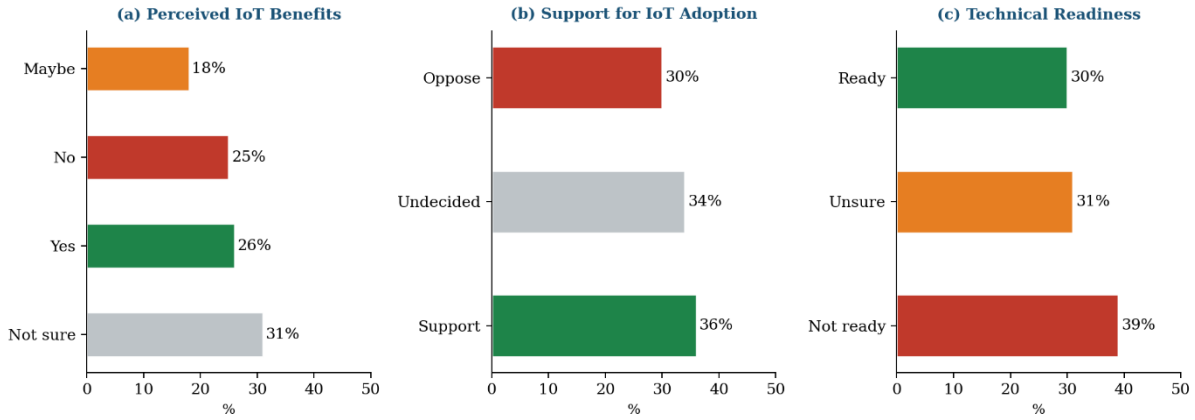


Figure 6. IoT Adoption Readiness across Three Dimensions, Technical Staff (n = 100)

4.7 Comparative Synthesis: Radar Analysis

Figure 7 synthesizes the comparison between both respondent groups across five key dimensions: service satisfaction, bin overflow severity, IoT support, challenge awareness, and system formality. The radar chart provides a visual representation of three major convergences (bad odour, delayed collection, negative system assessment) and highlights two significant divergences: residents score higher on challenge awareness dimensions related to daily lived experience, while technical staff score higher on system formality dimensions due to their institutional vantage point. The gap between overflow severity (both groups: high) and system formality (technical staff: 47% with formal systems; residents: not applicable) reveals the disparity between operational requirements and institutional readiness that the IoT framework must address.



Figure 7. Radar Comparative Analysis: Residents vs. Technical Staff across Five Dimensions

Table 2. Comparative synthesis of key findings across respondent groups

Indicator	Residents (n=120)	Technical Staff (n=100)
Bins at problematic fill levels	100%	82% frequently/always full
Collection < 2×/week	62.5%	N/A
Regular/frequent overflow	68.3%	N/A
Primary challenge cited	Bad odour (36.7%)	Bad odour (30%)
System rated Fair or Poor	63.3%	57%
No formal management system	N/A	53%
No full real-time monitoring	N/A	67%
Technical unreadiness for IoT	N/A	70% unready/uncertain
Support for IoT adoption	30.8%	36%

4.8 Discussion of findings

Alignment with Existing Literature

The findings are consistent with previous studies while providing empirical evidence from Mombasa County. Irregular collection, overflowing bins, and inadequate planning remain persistent challenges in Sub-Saharan Africa (Guerrero et al., 2013). Similarly, the observed

service deficits (68.3% regular overflows and 62.5% collection fewer than twice weekly) agree with findings from comparable East African cities (Wekisa & Majale, 2020).

The results also support the potential of IoT to improve waste collection. Previous studies reported 20–40% reductions in travel distance and 15–30% lower operational costs through real-time monitoring and optimized routing (Fang et al., 2015; Anagnostopoulos et al., 2015). In addition, the study highlights awareness and technical preparedness as important determinants of IoT adoption, extending the Technology Acceptance Model.

IoT Framework Design: Evidence-Based Implications

The findings informed seven design priorities (Table 3; Figure 8): ultrasonic fill-level sensing, automated overflow alerts, hybrid edge–cloud architecture, A* route optimization, a bilingual interface, capacity building, and sustainable financing. Together, these components address the technical and institutional requirements for IoT implementation.

Table 3. IoT System Design Implications Derived from Empirical Findings

Empirical Finding	Design Implication	Priority
100% bins at problematic fill levels	Ultrasonic fill-level sensors (primary layer)	Critical
67% without real-time monitoring	Cloud dashboard + overflow alerts at 80% capacity	Critical
23% limited infrastructure	Hybrid edge–cloud architecture (offline-capable)	High
70% technical unreadiness	Capacity-building programme + bilingual UI	High
38.3% refuse additional fees	Institutional / donor financing model	High
31.7% cite traffic disruption	A* routing with real-time congestion data	Medium
Only 30.8% residents support IoT	Community communication strategy pre-deployment	Medium

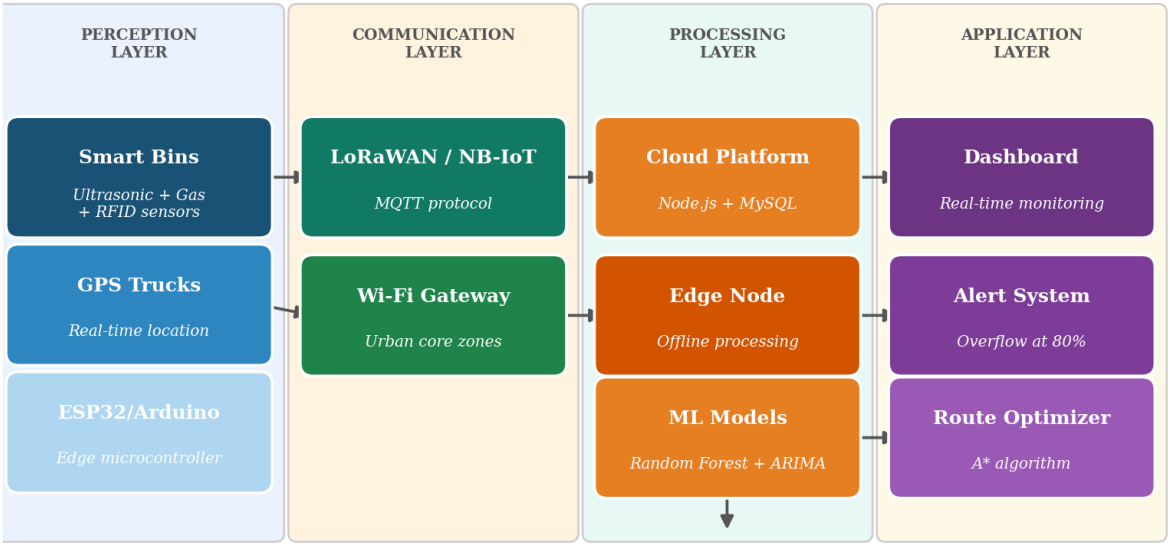


Figure 8. Proposed IoT-Based Waste Collection Framework, Four-Layer System Architecture

5. Conclusions and Recommendations

5.1 Conclusion

This study provides a comprehensive, empirically grounded assessment of IoT adoption feasibility for urban waste collection optimization in Mombasa County, Kenya. The empirical evidence demonstrates that the current waste management system shows notable deficiencies in operational effectiveness and service delivery, with universal bin overflow, grossly insufficient collection frequencies, deep institutional digital deficits, and limited stakeholder readiness for technological transition. The findings demonstrate the importance of adopting IoT-based waste management solutions while identifying key implementation challenges that must be addressed.

The proposed framework, combining ultrasonic fill-level sensing, GPS tracking, LoRaWAN/NB-IoT communication, and A* route optimization within a hybrid edge–cloud architecture, is intended to address the seven highest-priority design requirements identified in the data.

5.2 Recommendations

Based on the provided findings of this study, the following recommendations are suggested:

1. Deploy ultrasonic fill-level sensors and automated overflow alerts (80% capacity threshold) as an immediate first step in the highest-priority zones identified by the study.
2. Digitizing existing waste management systems, prioritizing organizations still relying on manual or paper-based approaches, ahead of full IoT rollout
3. Establish a capacity-building programme and bilingual (English–Swahili) user interfaces to raise technical readiness among staff, given that 70% report being unprepared or uncertain.
4. Adopt a hybrid edge–cloud architecture to sustain operation during the connectivity interruptions common in peri-urban zones.
5. Integrate A* route optimization using real-time traffic and congestion data to address the traffic-disruption concerns raised by residents.
6. Develop a community engagement and communication strategy prior to deployment, given that only 30.8% of residents currently support IoT adoption.
7. Secure sustainable financing through government or donor partnerships rather than resident fees, given that 38.3% of residents are unwilling to pay additional charges.
8. Pilot the framework in a limited number of high-priority zones before county-wide scale-up, supported by a formal monitoring and evaluation plan benchmarked against the baseline established by this study.

5.3 Suggestions for Further Research

Future research should assess the long-term performance of IoT-enabled waste management systems, undertake comparative studies across East African cities, and explore advanced machine learning approaches to enhance prediction accuracy in environments with intermittent network connectivity.

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