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Smart Waste Management in African Cities: Assessing Stakeholder Readiness for IoT-Based Waste Collection in Abuja, Nigeria

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Abstract

Rapid urbanisation has intensified municipal solid waste-management challenges in African cities, where conventional collection systems often rely on fixed schedules and limited information about waste accumulation. Internet of Things (IoT)-based collection can improve monitoring and responsiveness, but its effectiveness depends on stakeholder acceptance and institutional and infrastructural capacity. This study assesses stakeholder readiness for IoT-based waste collection in Gwarimpa Estate, Abuja, Nigeria, using a mixed-method case-study design. Data were obtained from 380 valid household questionnaires, interviews with 20 key stakeholders and field observations. Descriptive statistics, mean scores and the Relative Importance Index (RII) were used to analyse the quantitative data, while interview and observation evidence was thematically examined. Respondents reported favourable perceptions of IoT-enabled waste collection, particularly regarding collection frequency (mean = 3.80; RII = 0.760), response time (mean = 3.83; RII = 0.765) and overall service performance (mean = 3.67; RII = 0.734). Real-time monitoring and decision-making received the highest rating (mean = 4.12; RII = 0.824), while government incentives were identified as the most important implementation requirement (mean = 4.07; RII = 0.814). The findings indicate relatively strong social readiness but weaker infrastructural and institutional readiness. Successful implementation will therefore require reliable electricity and connectivity, technical capacity, sustainable financing, institutional coordination and sustained public engagement.

Keywords: Internet of Things; Smart waste management; Stakeholder readiness; Smart bins; Technology adoption; Municipal solid waste.

Introduction

Municipal solid waste management has become a major urban governance challenge as population growth, urban expansion and changing consumption patterns increase the volume and complexity of waste requiring collection and disposal. Global municipal solid waste generation was estimated at approximately 2.01 billion tonnes annually, with substantial growth projected as urban populations and consumption increase (Kaza et al., 2018). The challenge is particularly acute in developing countries, where waste-management systems are constrained by inadequate finance, infrastructure, institutional capacity and technical resources (Guerrero et al., 2013). Consequently, the problem is not only the quantity of waste generated but also the capacity of institutions to determine where waste is accumulating, when collection is required and how limited vehicles and personnel should be deployed.

African cities experience these challenges alongside rapid urbanisation and uneven infrastructure provision. Conventional collection systems often depend on predetermined schedules, manual inspection and complaints from residents. Such arrangements provide little real-time information and can result in vehicles visiting collection points with limited waste while other locations experience accumulation before the next scheduled collection. Overflowing containers, environmental nuisance, inefficient vehicle movements and unnecessary operating costs may consequently arise. These limitations have stimulated interest in digital technologies capable of linking residents, collection operators and municipal authorities through continuous information flows.

The Internet of Things (IoT) provides an important technological basis for this transition. IoT-enabled waste systems can connect fill-level sensors, communication networks, collection vehicles, geographic information systems and management platforms to provide information on the status and location of waste containers. Smart bins can support demand-responsive collection by identifying priority locations and providing information for adjusting collection routes and schedules. A systematic review by Sosunova and Porras (2022) identifies smart bins, sensor-based monitoring, waste-truck management, route optimisation, information exchange and stakeholder interaction as major components of smart waste-management systems. Recent studies similarly indicate that smart bins, IoT and artificial intelligence can improve monitoring, routing and operational decision-making, although technological integration, standardisation and institutional capacity remain important challenges (Zoumpoulis et al., 2024; Atofarati et al., 2025; Kumar et al., 2025).

Technical feasibility, however, does not necessarily imply implementation readiness. Reliable operation requires electricity, network connectivity, technical skills, maintenance, financing, data management, institutional coordination and user participation. Evidence from developing countries shows that social, economic, environmental and technical factors interact to shape the adoption of smart waste-management systems. African studies likewise emphasise infrastructure, finance, public participation and institutional arrangements as conditions for successful and scalable implementation (Atofarati et al., 2025).

Technology-adoption theories provide a useful basis for understanding stakeholder responses. The Technology Acceptance Model (TAM) identifies perceived usefulness and perceived ease of use as important determinants of information-technology acceptance (Davis, 1989; Davis et al., 1989). In waste management, perceived usefulness refers to the extent to which stakeholders expect IoT systems to improve collection, environmental conditions and service quality. The Unified Theory of Acceptance and Use of Technology (UTAUT) extends this

perspective through performance expectancy, effort expectancy, social influence and facilitating conditions (Venkatesh et al., 2003). Facilitating conditions are particularly relevant to municipal waste management because technically functional systems cannot operate reliably without appropriate infrastructure, personnel, finance and organisational procedures.

The distinction between acceptance and readiness is therefore important. Residents may support smart collection because they expect better services, while waste-management organisations may lack the resources to install and maintain the technology. Conversely, an organisation may possess technical infrastructure without sufficient public acceptance or institutional coordination. Readiness should consequently be understood as a socio-technical condition involving stakeholder willingness, perceived benefits, institutional capacity, infrastructure, finance and operational capability.

Nigeria provides an important context for examining this relationship. Waste management has historically been constrained by inadequate financing, institutional weaknesses, limited data, insufficient infrastructure and rapid urban growth (Ogwueleka, 2009; Ezeudu et al., 2021). Abuja, as the Federal Capital, has experienced substantial spatial and demographic expansion, increasing demand for reliable environmental services. Gwarimpa Estate, within Abuja Municipal Area Council, presents a useful case because of its substantial residential population, mixed land uses and demand for regular waste collection.

Although existing smart-waste research has extensively examined technological architecture, sensors, communication systems, routing algorithms and prototype development, comparatively less attention has been given to stakeholder readiness in African cities. This gap is important because smart waste management is not simply a technological intervention; it is a service-delivery system involving residents, government agencies, private operators, technology providers and other actors (Sosunova & Porras, 2022). This study therefore assesses stakeholder readiness for IoT-based waste collection in Gwarimpa Estate, Abuja. It examines perceived usefulness, expected service improvements, institutional and infrastructural readiness and willingness to support adoption. The study argues that technological opportunity alone is insufficient: successful adoption requires alignment between stakeholder acceptance and the institutional capacity to convert digital information into physical service improvements.

Materials and Methods

The study was conducted in Gwarimpa Estate, Abuja Municipal Area Council, Federal Capital Territory, Nigeria. The estate has developed from a predominantly residential area into a mixed-use urban district containing residential neighbourhoods, commercial activities, educational facilities and other urban services. These activities generate sustained waste and demand for reliable collection, making the area appropriate for assessing the potential transition from conventional to information-driven waste management.

A mixed-method case-study design was adopted. The quantitative component comprised a household questionnaire survey, while the qualitative component involved key-informant interviews and direct field observations. This combination was appropriate because readiness incorporates measurable perceptions as well as contextual institutional and operational conditions. Household responses provided evidence of acceptance and anticipated benefits, while professional interviews provided information on technical, financial, institutional and operational constraints.

The target population comprised household residents and relevant waste-management stakeholders, including waste-management officials, private waste operators, estate administrators and professionals with ICT or environmental-management expertise. Four hundred questionnaires were administered

using stratified and systematic sampling to obtain coverage across different residential areas. A total of 382 questionnaires were returned, representing a 95.5% retrieval rate. Two were excluded because of incomplete responses, leaving 380 valid questionnaires for analysis.

The questionnaire employed a five-point Likert scale from strongly agree to strongly disagree. Items covered conventional waste-management conditions, awareness of smart waste technologies, perceived usefulness, perceived ease of use, anticipated operational benefits and implementation requirements. Twenty key informants were purposively selected based on their direct professional involvement or relevant expertise. They comprised 10 waste-management officials, five estate administrators and five ICT/environmental specialists. Interviews addressed existing collection arrangements, equipment and vehicle availability, technical capacity, electricity and internet connectivity, financing, institutional responsibilities and the feasibility of sensor-enabled collection.

Field observations covered waste-collection points, bin condition and capacity, evidence of overflow, vehicle accessibility, indiscriminate disposal and supporting infrastructure. These observations were important because sensors cannot independently overcome physical constraints such as inaccessible collection points, inadequate container capacity or insufficient collection vehicles.

The measurement framework was informed by TAM and UTAUT. Perceived usefulness captured expected improvements in collection and environmental service delivery, while perceived ease of use represented anticipated system practicality. Additional dimensions included technological awareness, reliability, cost effectiveness and implementation readiness. Readiness was assessed through government support, public awareness, residents' willingness, skilled personnel, electricity, internet connectivity and funding.

Questionnaire reliability was assessed using Cronbach's alpha. The resulting coefficient of 0.869 exceeded the commonly accepted threshold of 0.70, indicating satisfactory internal consistency. Descriptive statistics and mean scores were used to summarise responses, while the Relative Importance Index (RII) was used to rank the relative strength of assessments:

$$\mathbf{RII = \frac{\Sigma W}{(A \times N)}}$$

where W is the weight assigned to each response, A is the highest possible weight and N is the number of respondents. For the five-point scale, A = 5. Higher RII values indicate stronger agreement or perceived importance. RII was used as a ranking measure rather than an inferential statistical test.

Interview responses were analysed thematically around institutional readiness, infrastructure, finance, technical capacity, operational response and public participation. Quantitative and qualitative findings were then compared to identify areas of convergence.

The study measures perceived readiness rather than actual system performance because a full-scale IoT system had not been deployed at the time of the research. Consequently, changes in response time, fuel consumption, vehicle kilometres, overflow frequency and collection costs could not be experimentally measured. The findings should therefore be interpreted as evidence of adoption readiness rather than causal evidence of IoT performance.

Results and Discussion

The survey generated 380 valid responses, comprising 206 males (54.2%) and 174 females (45.8%). The relatively balanced distribution provides representation of household perspectives across both genders.

Respondents generally recognised deficiencies in conventional waste management, producing a grand mean of 3.46 and RII of 0.693. Delays in removing accumulated waste, inadequate collection capacity, overflowing collection points, irregular collection and environmental nuisance were among the principal concerns. This finding is consistent with evidence that infrastructure, financing, institutional capacity and information deficiencies remain important constraints in Nigerian waste management (Ogwueleka, 2009; Ezeudu et al., 2021). Existing service deficiencies may increase the perceived usefulness of alternative systems, although dissatisfaction alone does not establish readiness to adopt IoT.

Perceived usefulness of IoT-based collection was generally high. Respondents associated smart bins with more efficient collection, faster response, reduced overflow and improved environmental conditions. This supports TAM's proposition that perceived usefulness contributes to technology acceptance (Davis, 1989). Importantly, respondents' assessment was based largely on expected practical service improvements rather than technological novelty.

Expected improvement in collection frequency recorded a grand mean of 3.80 and RII of 0.760. The specific proposition that smart bins could increase collection frequency received a mean of 4.19 and RII of 0.838. This indicates strong confidence that information about bin status could enable collection operators to respond more closely to actual demand, consistent with the operational logic of sensor-based monitoring and route optimisation (Sosunova & Porras, 2022; Chung et al., 2022). However, the expectation that waste would be collected before bins became full recorded a lower mean of 3.41 and RII of 0.682. The difference indicates that stakeholders distinguish between generating information and possessing the physical capacity to act on it. Sensors can identify a nearly full bin, but they cannot provide the vehicle, driver, fuel or institutional authority required for collection.

Perceptions concerning response time were similarly positive, with a grand mean of 3.83 and RII of 0.765. The expectation that IoT would reduce the time required to respond to full bins recorded a mean of 4.10 and RII of 0.820, whereas the expectation that collection vehicles would arrive more promptly recorded a lower mean of 3.55 and RII of 0.710. Again, respondents expressed greater confidence in information availability than in the physical response capacity of collection operators.

This distinction is important for interpreting TAM alongside UTAUT. TAM explains why stakeholders may value IoT because of its expected usefulness, whereas UTAUT draws attention to facilitating conditions (Venkatesh et al., 2003). The findings demonstrate that these dimensions must be considered together. Positive perceptions of the technology do not automatically overcome limitations in infrastructure, finance, staffing and organisational capacity.

Expected reduction in overflow produced a grand mean of 3.44 and RII of 0.688. The expectation that overflow incidents would become less frequent recorded a mean of 3.57 and RII of 0.714, while the proposition that smart bins would reduce overflowing bins recorded a mean of 3.30 and RII of 0.661. These ratings remain positive but are lower than those associated with collection frequency and response time. Stakeholders therefore did not regard smart bins as a stand-alone solution. Overflow is also determined by bin capacity, waste-generation rates, collection frequency, vehicle availability, road accessibility and disposal behaviour. IoT can improve detection but cannot eliminate these physical and behavioural factors. This supports recent reviews showing that smart-bin technologies have considerable potential but remain constrained by system integration, standardisation and technological maturity (Zoumpoulis et al., 2024).

The overall assessment of expected IoT impacts produced a grand mean of 3.67 and RII of 0.734. Real-time monitoring and decision-making ranked highest, with a mean of 4.12 and RII of 0.824. Improved collection efficiency recorded a mean of 3.83 and RII of 0.766, reduced operational costs 3.80 and RII

of 0.760, and increased resident satisfaction 3.72 and RII of 0.744. The dominance of real-time monitoring indicates that stakeholders perceive improved information as the principal value of IoT. Conventional systems frequently depend on fixed schedules and complaints, whereas sensor-based systems can provide continuous information about bin status and location, enabling managers to prioritise collection according to actual conditions (Sosunova & Porras, 2022).

The relatively lower rating for environmental cleanliness and public health (mean = 3.29; RII = 0.658) is also significant. Respondents did not assume that smart bins alone would solve environmental problems. Cleanliness depends on household behaviour, collection capacity, enforcement, disposal practices and wider environmental governance. IoT should therefore complement rather than replace conventional environmental-management measures.

Implementation readiness recorded a grand mean of 3.59 and RII of 0.718. Government incentives ranked first, with a mean of 4.07 and RII of 0.814, followed by public awareness (RII = 0.794), residents' willingness to adopt (RII = 0.783) and availability of skilled ICT personnel (RII = 0.782). These results indicate that institutional and social support are viewed as essential conditions for implementation.

The prominence of government incentives reflects the financial and governance requirements of smart waste management. Adoption involves initial expenditure on sensors, communication equipment, software and installation, as well as recurrent costs associated with connectivity, maintenance, replacement and technical support. Government intervention can reduce early adoption risks through targeted financing, procurement standards, regulatory support, infrastructure provision, data-governance arrangements and public-private partnerships.

Public awareness was also highly rated. Residents influence waste deposition, bin loading and the quality of the information generated by the system. Improper disposal outside designated points or excessive loading can undermine technically capable systems. Community engagement should therefore be incorporated into system design rather than treated as a post-implementation activity.

Residents' willingness to adopt was similarly high, suggesting a favourable demand-side environment in Gwarimpa. This is consistent with the role of perceived usefulness in TAM and behavioural intention in UTAUT. Nevertheless, willingness should not be equated with actual adoption because financial, infrastructural and institutional barriers may prevent implementation despite positive attitudes.

The importance attached to skilled ICT personnel further demonstrates that smart waste management introduces capabilities beyond conventional collection. Sensor installation, calibration, dashboard monitoring, data interpretation, network troubleshooting and maintenance require specialised competencies. Without these capabilities, smart-waste projects may remain temporary demonstrations rather than integrated municipal services.

The weakest supporting conditions included electricity reliability (mean = 3.22; RII = 0.644), technical knowledge among waste-management personnel (mean = 3.27; RII = 0.654), adequate funding (mean = 3.33; RII = 0.666) and internet connectivity (mean = 3.34; RII = 0.668). These findings represent the principal readiness constraints and correspond closely to UTAUT's facilitating-conditions construct. Similar barriers have been reported in developing-country smart-waste research, particularly regarding infrastructure, finance, technical capacity and institutional support.

Taken together, the findings reveal a distinct readiness gap. Gwarimpa demonstrates relatively strong social readiness but weaker infrastructural and institutional readiness. Stakeholders perceive IoT as useful, expect improved collection and express willingness to support adoption, while the conditions required for reliable operation receive lower ratings. The central challenge is therefore less about convincing stakeholders of the value of smart waste management and more about creating the conditions through which its potential can be realised.

The qualitative evidence reinforces this interpretation. Waste-management and administrative stakeholders identified collection vehicles, trained personnel, clear institutional responsibilities and sustainable financing as major concerns, while technical respondents emphasised electricity, connectivity, sensor maintenance and data management. Field observations further demonstrated that digital infrastructure must be integrated with physical waste-management conditions. Bin accessibility, container condition, collection-point location, overflow and vehicle access influence the ability of operators to respond to sensor-generated information. Installing sensors on poorly located or inaccessible bins would therefore not necessarily improve service performance.

The findings provide broader support for a socio-technical interpretation of UTAUT. Performance expectancy is reflected in expectations of improved monitoring and collection; effort expectancy concerns system practicality; social influence is reflected in public awareness and willingness; and facilitating conditions are represented by electricity, connectivity, funding, skills and government support. The evidence suggests that technology acceptance in municipal waste management should consequently be assessed alongside organisational and infrastructural capacity.

The results also have implications for smart-city policy in African cities. Smart-city initiatives often emphasise visible technological components such as sensors, dashboards and digital platforms, while less visible institutional elements may receive inadequate attention. Procurement arrangements, maintenance contracts, staff training, data ownership, response protocols, financing and accountability can ultimately determine whether sensor-generated information produces improved public services. Recent African research similarly emphasises context-sensitive implementation, infrastructure, financing and scalability as important conditions for smart-waste adoption (Atofarati et al., 2025). Evidence from Morocco further demonstrates the potential of IoT-enabled collection and dynamic routing while highlighting the need to integrate technology with existing collection infrastructure (Belhiah et al., 2024).

A functional IoT-based system in Abuja would require clearly defined stakeholder responsibilities. Government agencies should provide policy, regulation and oversight; private operators should undertake collection and operational response; technology providers should support sensors and digital platforms; telecommunications providers should facilitate data transmission; estate administrators should support local coordination; and residents should use collection facilities appropriately and participate in service monitoring. Smart waste collection should therefore be implemented as a service-delivery reform rather than an isolated technology project.

The principal limitation is that the proposed IoT system had not been deployed at full operational scale. Consequently, reported benefits represent stakeholder expectations rather than experimentally measured outcomes. The study also focuses on Gwarimpa Estate and should not be generalised mechanically to other African cities. Finally, descriptive statistics and RII establish the relative strength of perceptions but do not test causal relationships among acceptance, readiness and adoption. Future studies should therefore combine perception surveys with pilot implementation and longitudinal or inferential analysis.

Summary of Findings

The study found generally favourable stakeholder perceptions of IoT-based waste collection in Gwarimpa Estate. The strongest anticipated benefit was real-time monitoring and decision-making (mean = 4.12; RII = 0.824), followed by improved collection frequency and response time. This demonstrates that stakeholders primarily value IoT because of its capacity to improve information about waste conditions and support responsive service management.

Collection-frequency improvement recorded a grand mean of 3.80 (RII = 0.760), while response-time improvement recorded 3.83 (RII = 0.765). However, comparatively lower ratings for pre-emptive collection and prompt vehicle arrival demonstrate that respondents distinguish between digital information and physical operational capacity.

Implementation readiness recorded a grand mean of 3.59 (RII = 0.718). Government incentives ranked highest, followed by public awareness, residents' willingness and skilled ICT personnel. Electricity reliability, technical knowledge, funding and internet connectivity were comparatively weaker. The evidence therefore indicates strong social acceptance but less certain infrastructural and institutional readiness.

Overall, the findings support a socio-technical understanding of smart-waste adoption. Stakeholder acceptance provides an important foundation, but successful implementation requires infrastructure, financing, technical skills, institutional coordination and operational procedures capable of converting sensor-generated information into actual service improvements.

Conclusion

This study assessed stakeholder readiness for IoT-based waste collection in Gwarimpa Estate, Abuja, using 380 valid household questionnaires, interviews with 20 professional stakeholders and field observations. The findings demonstrate generally favourable perceptions of IoT-enabled waste management, particularly its potential to improve collection frequency, response time, monitoring and decision-making.

The most significant finding is that stakeholders place greater value on the information generated by IoT than on the technology itself. Real-time monitoring and decision-making received the highest rating, indicating that improved visibility of waste conditions is perceived as a major weakness of conventional collection systems. At the same time, lower ratings for vehicle responsiveness and supporting infrastructure show that information alone cannot guarantee improved service delivery.

The study identifies a clear readiness gap between social acceptance and implementation capacity. Government support, public awareness, technical skills, reliable electricity, internet connectivity and sustainable financing are necessary to convert positive attitudes into sustained adoption. The findings reinforce TAM and UTAUT while demonstrating that technology acceptance in municipal waste management should be examined alongside organisational and infrastructural readiness.

The principal policy implication is that smart waste management in African cities should be treated as a service-delivery and governance reform rather than a technology procurement exercise. Smart bins installed without response protocols, maintenance arrangements, financing mechanisms and clearly assigned institutional responsibilities are unlikely to produce sustained improvements. Abuja would therefore benefit from a phased implementation model that links technological deployment with institutional strengthening, infrastructure provision and stakeholder participation.

The study contributes to the emerging smart-waste literature by shifting attention from technological functionality towards stakeholder readiness in an African urban context. It demonstrates that the critical issue is not merely whether IoT technology is available, but whether the institutional, infrastructural and social conditions exist for it to generate reliable public-service outcomes. Future research should evaluate actual performance through pilot projects measuring response time, collection frequency, overflow incidence, vehicle kilometres, fuel consumption, operating cost, system uptime and resident satisfaction before and after implementation.

Recommendations

IoT-based collection should initially be introduced through a controlled pilot rather than immediate estate-wide deployment. Pilot locations should represent different residential and commercial conditions, with baseline measurements established before installation. This would permit objective assessment of changes in response time, collection frequency, overflow, vehicle movements and operating costs.

The pilot should employ an integrated monitoring platform rather than isolated smart bins. Fill-level sensors should transmit information to a central platform capable of identifying collection priorities and generating alerts. Where feasible, the system should be connected to GPS-enabled collection vehicles and route-planning functions. Clear procedures should specify who receives alerts, what fill level triggers collection, how priorities are established and how responses are recorded.

Government should establish an enabling environment through targeted financing, innovation support, appropriate procurement arrangements and minimum technical and operational standards. The strong rating assigned to government incentives indicates that public intervention may be important in reducing the financial and institutional risks associated with early adoption.

Public-private partnerships should be considered where they can distribute investment and operational responsibilities. Government agencies can provide regulation and oversight, while private operators and technology companies can contribute technical expertise, finance, software and maintenance. Partnership agreements should clearly establish equipment ownership, maintenance obligations, data ownership, service-level requirements and performance indicators.

Electricity and communication infrastructure should be treated as core components of the system. Where grid reliability is inadequate, low-energy sensors and solar-supported configurations may be considered. Communication technologies should reflect local network conditions and incorporate appropriate data-storage and recovery mechanisms to maintain functionality during temporary connectivity interruptions.

Technical capacity should be developed before full-scale implementation. Waste-management personnel should be trained in sensor maintenance, dashboard monitoring, data interpretation and response procedures, while dedicated technical support should address sensor, connectivity and software failures. Maintenance responsibilities should be explicitly assigned.

Public awareness should accompany technological deployment. Residents should understand the purpose and operation of smart bins, appropriate disposal practices and the relationship between household behaviour and system performance. Estate associations and community representatives should participate in pilot planning and monitoring and have accessible mechanisms for reporting overflowing bins, missed collections and equipment failures.

Performance evaluation should be based on measurable indicators rather than perceptions alone. Core indicators should include average response time, collection frequency, overflow incidence, vehicle kilometres, fuel consumption, collection cost, sensor accuracy, system uptime, missed alerts, maintenance expenditure and resident satisfaction. These indicators would establish whether anticipated benefits translate into measurable operational improvements.

Finally, Abuja should integrate IoT within a broader digital waste-management strategy. The long-term objective should not be the installation of smart bins as isolated technological assets but the creation of an information-based service system connecting residents, collection operators, government agencies and technology providers. Such an approach can progressively move waste collection from fixed schedules towards demand-responsive management while retaining the institutional structures necessary for reliable urban environmental services.

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