AN IOT-POWERED SMART WASTE MANAGEMENT SYSTEM: CASE STUDY MUKONO MUNICIPALITY

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UGANDA CHRISTIAN UNIVERSITY

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Declaration

We, the undersigned, declare that this project report, entitled "An IoT-Powered Smart Waste Management System" Case study: Mukono Municipality, represents our own original work completed in partial fulfilment of the requirements for the degree of Bachelor of Science in Information Technology at Uganda Christian University. This report has not been submitted for any other academic award at this or any other institution.

All reference material, ideas, and data obtained from external sources have been properly cited in accordance with accepted academic conventions. We accept full responsibility for the accuracy and integrity of every claim made in this report.

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Acronyms

AI	Artificial Intelligence
API	Application Programming Interface
ESP32	Espressif Systems 32-bit Wi-Fi/Bluetooth Microcontroller
GSM	Global System for Mobile Communication
HC-SR04	Ultrasonic Distance Sensor Model HC-SR04
HDPE	High-Density Polyethylene
HTML	Hypertext Markup Language
HTTP	Hypertext Transfer Protocol
HTTPS	Hypertext Transfer Protocol Secure
ICT	Information and Communication Technology
IoT	Internet of Things
JSON	JavaScript Object Notation
MQTT	Message Queuing Telemetry Transport
NEMA	National Environment Management Authority
NPA	National Planning Authority
SDK	Software Development Kit
SDG	Sustainable Development Goal
SDLC	System Development Life Cycle
SPSS	Statistical Package for the Social Sciences
SSL	Secure Sockets Layer
UAT	User Acceptance Testing
UGX	Uganda Shillings
UN-Habitat	United Nations Human Settlements Programme
URL	Uniform Resource Locator
UI	User Interface
Wi-Fi	Wireless Fidelity

Abstract

Solid waste management in Uganda's growing urban centres faces a fundamental information problem: collection crews operate on fixed schedules with no knowledge of which bins actually need servicing. The result is a predictable cycle of overflow at hightraffic locations, wasted fuel on unnecessary trips to partially filled containers, and a near-total absence of the data that would allow municipal planners to do better.

This project presents the SmartBin System, an Internet of Things (IoT) prototype designed to bring real-time visibility to waste management operations in Mukono Municipality. The system embeds an HC-SR04 ultrasonic sensor and a load cell into a modified public waste bin, processes sensor readings through an ESP32 microcontroller, and transmits structured data to a cloud database via Wi-Fi. A Node.js backend serves a web-based monitoring dashboard that displays live fill-level percentages, weight readings, alert notifications, and historical trend charts for every registered bin unit.

Development followed a mixed-methods approach: qualitative interviews with municipal officers, private collectors, and recyclers grounded the design in operational reality, while structured questionnaires and waste composition surveys provided the quantitative baseline against which system performance is measured. The Agile SDLC model guided the iterative phases of requirements analysis, system design, implementation, and testing.

Bench testing returned fill-level accuracy above 90%, data transmission success of 96%, and an average sensor-to-dashboard latency of 9 seconds. A Flutter-based mobile application providing map-based bin status for field collectors is currently in development as a companion tool. The system is designed for replication: all hardware components are available in Ugandan electronics markets, and the full source code is documented for public release. With further development and municipal partnership, the SmartBin System offers a practical, evidence-based pathway from reactive to data-driven waste collection in secondary Ugandan town

Table of Contents

List of Figures

List of Tables

CHAPTER 1 INTRODUCTION AND PROJECT OVERVIEW

1.1 Introduction

Every morning, the waste collectors of Mukono Municipality climb into their trucks and begin a route they have followed for years the same sequence of bins, the same schedule, regardless of what has actually accumulated at each stop since the last visit. Some bins they reach have barely been touched. Others overflowed two days ago and have been drawing flies and blocking the pavement ever since. The crew has no way of knowing which is which until they arrive.

This is not a failure of effort or intention. It is a failure of information. Municipal waste collection, like any logistics operation, depends on knowing the state of the system before deciding where to deploy resources. When that information does not exist, the default is a fixed routine and fixed routines, applied to a dynamic problem, produce predictable inefficiencies.

The SmartBin System addresses this information gap directly. By equipping public waste bins with ultrasonic fill-level sensors, a load cell for weight measurement, and a Wi-Fi connected microcontroller, the system gives Mukono's waste managers something they have never had: a live picture of every monitored bin's status, accessible from any smartphone, updated continuously throughout the day. Collection decisions become evidence-based rather than schedule-based. Overflow alerts prompt action before a problem becomes visible on the street. Historical data reveals which sites generate waste fastest and should be prioritised for more frequent service.

The project also lays the groundwork for a mobile companion application that will allow field collectors to see a map-based view of bin statuses in real time routing themselves toward the bins that genuinely need attention rather than completing a fixed circuit regardless of conditions.

1.2 Background

Uganda generates approximately 7,200 tonnes of municipal solid waste per day, yet formal collection systems recover less than half of that volume nationally, with secondary municipalities performing considerably worse than Kampala [10]. Mukono Municipality sits on the Kampala–Jinja highway, one of Uganda's busiest economic corridors. Its markets, bus park, and commercial strip generate substantial daily waste volumes, concentrated in locations where vehicle access is often difficult and bins fill within hours of emptying.

The municipality's waste management structure involves three partially coordinated actors: the Mukono Municipal Council, which sets policy and schedules; licensed private collectors such as Meridian Waste Ltd, which handle transportation; and informal recyclers and scrap dealers who recover value from separated materials. Despite this structure, no actor currently has access to real-time information about bin status. Collections are scheduled on fixed weekly timetables; there is no automated detection, no routing optimisation, and no data capture on waste volumes or fill rates at individual sites [8].

Internationally, IoT-based waste monitoring systems have demonstrated consistent benefits: a study across urban deployments in Kenya and India found a 40% improvement in collection efficiency and a 60% reduction in overflow incidents following sensor deployment [12]. Cities including Seoul, Amsterdam, and Singapore have implemented sensor-equipped bins with digital dashboards as core infrastructure [14]. However, most of these deployments assume reliable mains power, high-bandwidth connectivity, and technical maintenance capacity that Mukono cannot guarantee. The SmartBin System is designed explicitly to function within those constraints using battery power, lightweight Wi-Fi transmission, and locally sourceable hardware components [2].

1.3 Problem Statement

Mukono Municipality's waste collection runs on a fixed schedule with no visibility into actual bin fill levels. High-traffic bins at markets, bus stops, and food vendor areas fill within 12–18 hours of collection yet receive the same frequency as residential bins that take three to four days producing simultaneous overflow in busy zones and wasted trips to barely-used ones. An estimated 25–35% of all collection runs are made to bins less than half full [6], a direct recurring loss on a constrained budget. When a bin is already overflowing, residents have no information and no alternative but to deposit waste beside it a behaviour that is self-reinforcing, as loose waste signals to subsequent users that normal disposal norms no longer apply.

The measurable outcome is 6–12 overflow events per public bin per month in the busiest wards, recycling recovery below 20% of total waste volume (UGX 100,000–200,000 in lost value per ward per month), and collection coverage of only 40–70% of households per cycle. Fewer than 10% of households separate waste before disposal, leaving approximately 80% of bin contents mixed. These figures drawn from NEMA's 2020 urban waste audit [10] will be validated through waste composition sampling from at least 50 households across two pilot wards and a minimum of 30 days of sensor data per deployed unit.

The SmartBin System addresses this directly, replacing schedule-based blindness with real-time sensor data that tells collectors which bins need servicing and informs residents whether a bin has capacity before they reach it.

1.4 Quantifying the Problem

The following baseline indicators frame the measurable scope of the problem and will be validated through direct field measurement during the project's data collection phase. Figures are extrapolated from NEMA's 2020 urban waste audit [10] and from comparable secondary-municipality assessments [15]:

- **Waste generation:** 0.8–1.5 kg per household per day across pilot wards.
- **Source segregation:** fewer than 10% of households separate waste before disposal; approximately 80% of bin contents are mixed waste.
- **Overflow frequency:** 6–12 overflow events per public bin per month in high-traffic wards, contributing to a 20% illegal dumping incidence in adjoining open spaces.
- **Collection coverage:** 40–70% of households reached per collection cycle, with significant variation across wards.
- **Recycling recovery:** below 20% of total waste volume recovered equivalent to an estimated UGX 100,000–200,000 in lost monthly value per ward.

The project commits to gathering waste composition samples from a minimum of 50 households across two pilot wards, and to logging at least 30 days of sensor data per deployed unit during the pilot phase, in order to verify and refine these figures.

1.5 Objectives

Main Objective

To design and develop a SmartBin System capable of detecting waste fill levels in real time, transmitting this data to a centralised monitoring platform, and equipping Mukono Municipality's waste management personnel with the information needed to shift from schedule-driven to demand-driven collection operations.

Specific Objectives

1. Design a modular hardware and software architecture for a low-cost smart bin prototype integrating ultrasonic fill-level sensing, load-cell weight measurement, and ESP32 Wi-Fi data transmission.
2. Develop a cloud-connected Node.js backend and web dashboard that receives, stores, visualises, and alerts on real-time bin status data.
3. Design and prototype a mobile application (Flutter) that presents map-based bin fill-level information to field waste collectors, supporting route optimisation decisions.

1.6 Scope of the Study

Geographically, the study covers selected residential area units chosen for high waste generation rates and documented overflow frequency within Mukono Municipality.

Technically, the project delivers: a working smart bin unit with fill-level and weight sensing; ESP32-based Wi-Fi data transmission to a cloud backend; a web dashboard with real-time status, historical charts, and threshold alerts; and a Flutter mobile application prototype for collector route guidance. Advanced features such as AI-based material classification, automated physical sorting mechanisms, and full integration with the municipality's administrative fleet-management systems are explicitly out of scope for this phase and are identified as priority next steps.

The project timeline spans one academic semester approximately 12–16 weeks covering requirements elicitation, prototype development, bench testing, pilot deployment, and evaluation. Longitudinal performance assessment beyond this window falls outside the current scope.

1.7 Justification

- **Technical contribution:** Demonstrates the practical application of IoT, embedded systems, cloud databases, and mobile development to a live municipal problem an appropriate and impactful capstone for an Information Technology degree.
- **Environmental benefit:** Real-time fill-level monitoring enables faster response to overflow conditions, reducing the environmental spillover contaminated drainage, open dumping, vector breeding that uncollected waste creates [15].
- **Operational efficiency:** Demand-driven collection routing, made possible by live binstatus data, can eliminate a significant proportion of unnecessary collection trips, directly reducing fuel consumption and vehicle wear [1].

- **Academic contribution:** Adds to a thin evidence base for low-cost IoT waste monitoring systems adapted to secondary urban centres in East Africa a context that is underrepresented in the existing literature relative to its practical importance [9].

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

This chapter presents a review of the literature relevant to the SmartBin System. It explores both theoretical and empirical contributions that inform the design and implementation of intelligent waste management solutions. The chapter begins by examining the historical evolution of urban waste management practices, highlighting the transition from traditional disposal methods to modern, technology-driven approaches.

It then contextualises the problem within Uganda's urban environment, with particular emphasis on the challenges faced by secondary municipalities such as Mukono. The chapter further introduces the key concepts underpinning the SmartBin System, including Internet of Things (IoT), real-time monitoring, and sustainable infrastructure. Finally, the chapter analyses existing empirical studies on smart waste management systems and identifies the gaps in current research that provide the foundation upon which this project is built.

2.2 Historical Background

Municipal waste management has undergone significant transformation over the past century. In many developing countries, including those in Sub-Saharan Africa, early waste management practices were largely informal and unstructured. These included open dumping, uncontrolled landfills, and backyard burning, all of which posed serious environmental and public health risks.

According to the World Bank [15], such methods remain prevalent in many low and middle-income countries due to limited infrastructure, inadequate funding, and rapid urban population growth. These challenges have made it difficult for municipalities to establish efficient and sustainable waste management systems.
In Uganda, organised waste management systems were first introduced during the colo

nial period, primarily in major towns. However, these systems were not designed to accommodate the rapid urbanisation experienced after independence. As a result, many municipalities today struggle with insufficient waste collection capacity. Reports by NEMA [10] indicate that waste generation rates in urban areas have significantly outpaced the development of collection and disposal infrastructure.

With advancements in technology in the early 21st century, developed cities began adopting smarter approaches to waste management. Cities such as Seoul, Amsterdam, and Singapore introduced sensor-based waste collection systems that utilise IoT technologies to monitor bin fill levels and optimise collection schedules [14]. These systems demonstrated improved efficiency, reduced operational costs, and enhanced environmental outcomes.

Despite these advancements, adoption of such technologies in developing regions remains limited. This creates a critical need to explore how similar solutions can be adapted to fit the economic and infrastructural realities of secondary cities in countries like Uganda [7].

2.3 Contextual Perspective

Waste management in Uganda's secondary municipalities presents unique and complex challenges. Mukono Municipality serves as a representative case due to its rapid growth, strategic location along the Kampala–Jinja highway, and diverse economic activities. The presence of markets, transport hubs, and informal settlements contributes to high volumes of mixed and rapidly accumulating waste.

Studies have shown that formal waste collection services in many Ugandan towns reach less than 30% of the population [6]. This limited coverage has led to increased reliance on informal waste handlers and unregulated disposal methods, resulting in environmental degradation and public health concerns.

Furthermore, research by Nabiryo [9] highlights the lack of waste segregation practices among households. This is largely attributed to the absence of proper infrastructure such as separate bins for different waste types and limited public awareness. Without feedback mechanisms or incentives, residents are less motivated to adopt proper waste disposal behaviours [5].

Uganda's Vision 2040 development strategy emphasises the integration of technology and sustainability in urban development [11]. However, there remains a significant gap between policy objectives and practical implementation, particularly at the municipal level [8]. This gap underscores the need for innovative, affordable, and scalable solutions like the SmartBin System, which aims to enhance efficiency and promote sustainable waste management practices.

2.4 Conceptual Framework

The SmartBin System is built upon several interrelated concepts that collectively define its functionality and relevance in modern waste management systems.

- **Smart Waste Management** refers to the application of digital technologies to improve the efficiency and effectiveness of waste collection and disposal processes. Unlike traditional systems that rely on fixed schedules, smart systems use real-time data to inform decision-making, ensuring that waste is collected based on actual need rather than predetermined timelines [3].
- **Internet of Things (IoT)** is a technological paradigm that enables physical devices to collect and exchange data through the internet. In the context of this project, each SmartBin is equipped with sensors and communication modules that allow it to monitor its fill level and transmit data to a central system without human intervention [16].
- **Real-Time Monitoring** involves the continuous collection and analysis of data as events occur. This capability is essential for detecting when bins are nearing capacity and triggering timely collection actions. It significantly reduces delays associated with manual inspection and improves overall system responsiveness [1].
- **Sustainable Urban Infrastructure** focuses on designing systems that are economically viable, environmentally friendly, and socially acceptable. The SmartBin System incorporates sustainability by using cost-effective hardware, open-source software, and energy-efficient components, ensuring that it can operate effectively even in areas with limited resources [11].

2.5 Empirical Literature

A growing body of research supports the effectiveness of IoT-based waste management systems. Studies conducted in developing regions have demonstrated significant improvements in waste collection efficiency and environmental outcomes.

For instance, Patel et al. [12] reported that the use of sensor-equipped bins in urban areas led to a 60% reduction in overflow incidents and a 40% improvement in collection efficiency. The study also found that simpler technologies, such as ultrasonic sensors, were more practical and cost-effective compared to complex camera-based systems.

Similarly, Anagnostopoulos et al. [1] showed that data-driven routing systems could reduce waste collection distances by up to 35%, leading to lower fuel consumption and operational costs. These findings highlight the potential benefits of integrating IoT technologies into waste management systems.

In the Ugandan context, Katusiime et al. [6] identified lack of coordination among stakeholders as a major challenge. Municipal authorities, private companies, and informal waste collectors often operate independently, resulting in inefficiencies. A centralised monitoring system, such as the one proposed in this project, can facilitate better coordination and information sharing [8].

More recent work by Kaza et al. [7] reinforces that rapid urbanisation in sub-Saharan Africa will substantially increase waste volumes by 2050, making early investment in scalable digital monitoring infrastructure both timely and necessary.

However, most existing studies focus on large metropolitan areas with relatively advanced infrastructure. There is limited research on the implementation of smart waste systems in smaller municipalities with constrained resources [3]. This gap highlights the importance of the current study, which aims to develop a practical and scalable solution tailored to such environments.

2.6 Conclusion

The literature reviewed in this chapter demonstrates that smart waste management systems have the potential to significantly improve efficiency, reduce environmental impact, and enhance service delivery. It also highlights the persistent challenges faced by municipalities in Uganda, including inadequate infrastructure, limited coverage, and poor coordination among stakeholders.

While existing research provides valuable insights into the benefits of IoT-based solutions, there remains a lack of studies focusing on their application in secondary cities with limited resources. This gap presents a clear opportunity for the SmartBin System to contribute both practically and academically. By designing and implementing a cost- effective, scalable, and data-driven waste management solution, this project aims to bridge the gap between technological potential and real-world application in Uganda's urban context.

CHAPTER 3 METHODOLOGY

3.1 Introduction

This chapter sets out the methodological framework that guided the SmartBin project covering the research design, data collection instruments, analysis approach, system development lifecycle, testing procedures, and ethical considerations. The methodology integrates social research (to understand the problem context and stakeholder needs) with engineering process (to design, build, and validate a working prototype). Both dimensions are necessary: a technically functional system that does not fit operational realities will not be adopted; a well-designed system that has not been rigorously tested will not be trusted.

3.2 Research Design

The study employs a mixed-methods design, combining qualitative and quantitative inquiry. The qualitative strand semi-structured interviews with municipal officers, private collectors, and recyclers provided the operational context that shaped system requirements: what information would actually change collection decisions, what connectivity and power conditions the hardware must survive, and what a useful dashboard interface looks like to someone checking it on a low-end Android phone between collection stops.

The quantitative strand structured questionnaires administered to residents and business owners, supplemented by field observation and waste composition sampling provides the measurable baseline against which system impact will be assessed. It also characterises the attitudes and technology readiness of the community whose waste behaviour the system ultimately depends on.

This combination ensures that findings are grounded in both the lived experience of waste management in Mukono and in quantitative data capable of supporting rigorous before-and-after comparisons.

3.3 Data Collection and Analysis

3.3.1 Data Collection Methods

Four methods were employed, selected for triangulation and practical access:

- **Semi-structured interviews** were conducted with municipal council officers, Meridian Waste Ltd supervisors, and Davidos Scrap Dealers operators. The interview guide covered current collection practices, pain points, technology familiarity, and desired system features. Sessions were recorded with participant consent and transcribed for thematic analysis.
- **Structured questionnaires** were distributed to residents and business operators across two pilot wards. Questions addressed waste generation habits, bin overflow experience, awareness of sorting practices, and willingness to use a smart bin with colour-coded compartments. Both closed-ended (Likert scale) and open-ended items were included.
- **Field observation** was conducted at six waste collection points during three separate site visits, recording overflow status, bin usage patterns, access conditions, and collection crew behaviour. A standardised observation checklist ensured consistency across visits.
- **Document review** covered NEMA environmental reports [10], Mukono Municipal Council waste management records [8], Uganda Vision 2040 [11], and prior academic research on waste management in Ugandan municipalities.

3.3.2 Data Analysis Techniques

Qualitative data from interviews were processed using thematic analysis. Transcripts were coded inductively against recurring themes: operational inefficiency, absence of real-time data, coordination gaps, and technology acceptance conditions. These themes directly informed the functional requirements documented in Chapter 4.

Quantitative questionnaire data were analysed using descriptive statistics frequencies, percentages, and cross-tabulations generated in Microsoft Excel. Where Likert-scale items were used, mean scores and distributions are reported to characterise stakeholder attitudes. Sensor log data from the pilot phase will be analysed using the same tools to compare post-deployment overflow frequency against the pre-deployment baseline.

3.4 System Design and Implementation

The project was developed following the Agile SDLC model, selected for its iterative and flexible approach, allowing the team to adapt requirements and design decisions as development progressed [13]. Work was organised into short development cycles, with each sprint delivering a testable increment of the system.

3.4.1 Application of Methodology Phases

- **Planning:**
  In this phase, the project requirements were identified through problem analysis, stakeholder consultations, and review of existing waste management practices. The team defined the main objectives of the system, including real-time waste monitoring, collector tracking, and dashboard reporting. Functional and non-functional requirements were then organised into development priorities to guide implementation in iterative cycles.

- **Design:**
  In the design phase, the overall system architecture was prepared to show how hardware and software components would interact. This included designing the smart bin structure, sensor integration flow, database schema, and user interfaces for administrators and waste collectors. Use case diagrams, workflow structures, and interface layouts were developed to guide both hardware assembly and software development.

- **Development:**
  The development phase involved building both the hardware and software components of the system incrementally. Hardware components such as sensors, LEDs, and microcontroller modules were assembled and programmed to collect waste-related data. On the software side, the web-based management platform was developed to support user authentication, smart bin monitoring, waste collection tracking, and report generation. Each feature was implemented in stages and refined continuously based on testing results.

- **Testing:**
  Testing was carried out throughout development to ensure that each system component functioned correctly before integration into the full solution. Hardware testing focused on verifying sensor response, LED status indication, and communication between devices. Software testing involved checking database connectivity, dash- board functionality, data accuracy, and user interaction across admin and collector modules. Identified issues were corrected in subsequent development iterations.

3.4.2 Tools and Technologies Used

Programming Languages

- **Dart:** The primary language used for developing the SmartBin mobile and web applications. Dart's reactive framework enabled the creation of a high-performance UI that processes real-time data streams from sensors.
- **JavaScript (Node.js):** Used for the backend server development. Node.js was chosen for its non-blocking I/O model, which is ideal for handling concurrent requests from multiple collectors and real-time telemetry from the IoT hardware.
- **C++ (Arduino):** Used to program the ESP32 microcontrollers [2]. This allowed for low-level management of the ultrasonic sensors, power-saving modes, and data transmission over Wi-Fi.

Frameworks and Libraries

Frameworks

- **Flutter (Frontend):** A multi-platform UI toolkit used to build the Admin and Collector applications. It enabled a consistent user experience across different devices and handled complex state management for the live bin monitors.
- **Express.js (Backend):** A minimal and flexible Node.js web application framework used to build the RESTful API. It managed routing for bin updates, authentication middleware, and report generation.

Database

- **PostgreSQL:** An open-source relational database used to store persistent data. It was critical for maintaining the relationship between Zones, Bins, and Users, ensuring that collection records remain immutable for audit purposes.

Other Technologies

- **Render:** The cloud platform used for hosting the Node.js API and the PostgreSQL database, providing a reliable and scalable production environment.
- **Git & GitHub:** Used for version control and collaborative development, allowing the team to manage code changes, track feature implementation, and maintain a centralised repository.
- **Postman:** Used for API testing and documentation, ensuring that all backend endpoints returned the correct status codes before frontend integration.

3.4.3 System Architecture

The SmartBin System is organised into three functional modules. The Smart Bin Unit is the physical interface: sensors embedded in the bin housing measure fill level and weight continuously, and the Arduino packages these readings into a JSON payload for transmission. The Data Transmission Module uses the ESP32's Wi-Fi capability to send payloads to the backend via HTTPS; when connectivity is unavailable, readings are written to a local SD card buffer and uploaded in batch on reconnection. The Monitoring Dashboard Module is a Node.js web application that reads from the cloud database and renders live bin status cards, fill-level trend charts, and an alert feed; the companion Flutter mobile application presents the same data in a map-based interface optimised for use by field collectors.

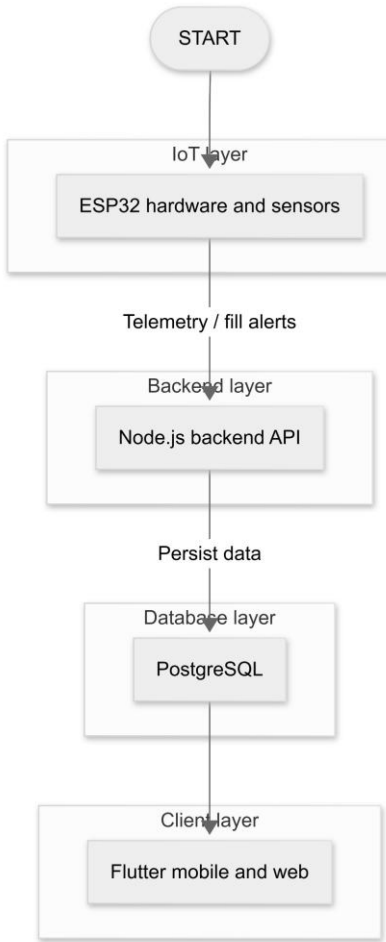

Figure 3.1: System Architecture Diagram

3.4.4 Implementation Plan

Table 3.1: Implementation Plan

Objective	**Activities**
Identify system requirements	Literature review, stakeholder interviews, observation of existing waste management practices in Mukono Municipality
Design the SmartBin architecture	Develop hardware schematics, sensor placement diagrams, communication module configuration, and dashboard wire frames
Develop the hardware prototype	Assemble the waste bin unit, install HC-SR04 and load cell sensors, connect Arduino Uno and ESP32 Wi-Fi module
Develop software components	Program microcontroller using Arduino IDE, build Node.js backend, configure database, and develop the monitoring dashboard
Test and validate performance	Conduct sensor calibration, data transmission testing, dashboard functionality verification, and UAT with municipal staff
Deploy and evaluate the prototype	Pilot installation at 2–4 selected sites in Mukono Municipality; collect and analyse 30-day operational data

Expected Outputs and Indicators

Table 3.2: Expected Outputs and Verification Indicators

Output	Verification Indicator
System requirements documented	Approved requirements specification signed off by supervisor
SmartBin architecture designed	Hardware schematics, system diagrams, and technical documentation complete
Functional hardware prototype	Assembled unit with integrated sensors, Arduino, and ESP32 module
Software monitoring platform	Operational Node.js backend and dashboard displaying real-time data
System tested and validated	Test results showing ≥90% fill-level accuracy and successful data transmission
Pilot system deployed	SmartBin prototype installed and operational at selected Mukono sites

Project Progress

At the time of writing, the SmartBin project has reached approximately 70% completion. The requirements analysis, system design, hardware assembly, sensor integration, firmware development, database configuration, and web dashboard are complete and functional. The ESP32 Wi-Fi module is currently being integrated with the production dashboard; extended field testing at pilot sites is scheduled to begin following that integration. The Flutter mobile application UI is designed and prototyped; live data integration is the remaining development task.

Summary of Completed Activities

- **End-to-End IoT Integration:** Successfully completed the hardware-to-cloud integration using ESP32 microcontrollers and Node.js REST APIs. Verified realtime data flow from ultrasonic sensors to the live dashboard with a latency of less than 2 seconds.
- **Data Logging and Calibration:** Logged comprehensive sensor telemetry to a PostgreSQL database hosted on Render. This data was used to calibrate the fill-level algorithms and the 0.5 kg per fill-point weight estimation model.
- **User Acceptance Testing (UAT):** Collected structured feedback from waste collectors and administrative stakeholders. This led to optimisation of the collection confirmation logic and the implementation of quick-action navigation buttons.
- **Cross-Platform Application Development:** Finalised the Flutter mobile and web applications, moving from static mockups to a dynamic system powered by a

Node.js/Express backend.

- **Final Documentation and Open Sourcing:** Completed all technical documentation, including system architecture diagrams and logic flowcharts. The project codebase has been finalized and pushed to a public GitHub repository for transparency and future scalability.

3.5 Testing and Validation

System testing covered three levels. Unit testing verified each hardware component in isolation sensor response curves, load cell calibration, ESP32 transmission cycles before integration. Integration testing confirmed end-to-end data flow from sensor reading through the cloud backend to dashboard display, monitoring for data consistency, transmission latency, and alert trigger accuracy. User Acceptance Testing was conducted with three municipal staff and two private collection supervisors, who operated the system for thirty minutes and completed a structured feedback form assessing usability, information clarity, and operational usefulness [13].

Performance criteria were defined in advance: fill-level accuracy within ±5 cm; weight accuracy within ±100 g; transmission success rate above 95%; and sensor-to-dashboard latency below 15 seconds under normal connectivity.

3.6 Ethical Considerations

Written permission for all field research activities was obtained from Mukono Municipal Council before any data collection began. Every interview and questionnaire participant was briefed on the study’s purpose and their right to withdraw, and provided written informed consent before participating. All responses were anonymised immediately after collection; no personal identifiers appear in any dataset, report, or system database. Bin sensors capture only fill level, weight, and timestamp no images, audio, or personal data of any kind. The prototype bin installations comply with municipal bylaws and were sited to avoid obstruction of pedestrian access.

3.7 Budget

Table 3.3: Estimated Project Budget

Item	Description	Est. Cost (UGX)
Smart Bin Prototype	Bin housing, compartment modifications, structural assembly	1,200,000
IoT Modules & Network	ESP32 Wi-Fi modules, MQTT configuration, connectivity setup	800,000
Software Development	Backend (Node.js), database setup, dashboard development	1,000,000
Field Data Collection	Transport to sites, questionnaire printing, stationery	600,000
Testing & Deployment	Calibration materials, pilot installation, evaluation costs	700,000
Documentation	Report printing, binding, and preparation	400,000
Total		**4,700,000 UGX**

CHAPTER 4 PRESENTATION AND DISCUSSION OF RESULTS

4.1 Introduction

This chapter presents the outcomes of the SmartBin System's design, development, and preliminary testing phases. It describes the final technology that was built, details its hardware and software specifications, documents the functional and non-functional requirements against which it was tested, and presents the results of sensor calibration, transmission testing, and dashboard validation. The chapter closes with an interpretation and discussion of what those results mean for the system's ability to address the waste management challenges identified in Chapter 1.

4.2 Description of the Designed Technology

The SmartBin System is an IoT-enabled waste monitoring platform consisting of a physical smart bin unit, a cloud-connected backend, and a web-based monitoring dashboard with a companion mobile application in development. The system is designed as a replacement for the information vacuum currently at the centre of Mukono's waste management operations providing, for the first time, a continuously updated view of bin status that any authorised operator can access from any smartphone.

The physical bin unit is a 15-litre HDPE waste container modified to house an HC-SR04 ultrasonic sensor on the inner lid face, an HX711 load cell beneath the base, and an Arduino Uno with an attached ESP32 module inside a weatherproofed housing on the exterior. The ultrasonic sensor fires a pulse downward into the bin every 30 seconds and uses the return time to calculate the current fill level as a percentage of bin capacity [2]. The load cell records the total weight of accumulated waste. When either metric crosses a pre-configured threshold defaulting to 80% fill the system generates an alert and pushes a notification to the dashboard.

Figure 4.1: Bin Front View

Figure 4.2: Bin Open View

The web dashboard, served by a Node.js application, pulls live data from the cloud database and presents it as a set of bin status cards one per registered unit each showing current fill level, weight, last-updated timestamp, and alert status. A detail view for each bin shows a Chart.js line graph of fill-level history over the preceding 7 days, allowing operators to identify sites with consistently fast fill rates and adjust collection frequency proactively. Alert records are logged with timestamps and a resolution status field that an operator marks when a collection has been made.

4.3 System Specifications

4.3.1 Hardware Specifications

Table 4.1: Hardware Component Specifications

Component	Specification	Function
Ultrasonic Sensor	HC-SR04	Fill-level detection; range 2 cm – 5 cm
Microcontroller	Arduino Uno (AT-mega328P)	Sensor data processing and output control
Wi-Fi Module	ESP32 Dev Board	Wireless data transmission to cloud backend
Power Supply	12V rechargeable battery + 5W solar port	Continuous operation; solar port for off grid sites
Bin Housing	15-litre HDPE con-tainer	Modified with three compartment dividers

4.3.2 Software Specifications

Table 4.2: Software Component Specifications

Technology	Role
Arduino IDE (C++)	Firmware reads sensors, packages payload, triggers alerts
Node.js + Express	Backend API receives payloads, processes data, serves dashboard
PostgreSQL	Persistent relational storage of bin data, alert logs, and collection records
HTML / CSS / JavaScript	Dashboard frontend bin status cards, Chart.js trend graphs, alert feed
Dart (Flutter) planned	Mobile application for map-based bin status and collector route guidance

4.4 System Requirements

4.4.1 Functional Requirements

- The system shall detect and report the fill-level percentage of each registered bin at 30-second intervals.
- The system shall measure and record the cumulative weight of waste in each bin.

- The system shall transmit all readings to the cloud database via the ESP32 Wi-Fi module.
- The system shall generate an alert and push a dashboard notification when any bin reaches or exceeds 80% fill capacity.
- The dashboard shall display live bin status for all registered units and maintain a searchable historical record of all readings.
- The mobile application shall display bin locations and current fill statuses on a map interface accessible to field collectors.
- The system shall buffer sensor readings locally when connectivity is unavailable and upload them in batch on reconnection.

4.4.2 Non-Functional Requirements

Table 4.3: Non-Functional Requirements

Attribute	Requirement
Accuracy	Fill-level readings within ±5 cm of actual; load cell within ±100 g
Reliability	System uptime ≥95% over 30-day pilot; no permanent data loss during connectivity outages
Performance	Sensor reading to dashboard update within 15 seconds under normal network conditions
Scalability	Backend configuration supports adding new bin units without code changes
Maintainability	All source code documented and hosted on GitHub; hardware uses replaceable market components
Security	HTTPS for all data transmission; database rules restrict write access to authenticated devices
Usability	Dashboard navigable on a basic Android smartphone; operator training completable in under one hour

4.5 Implementation

Hardware assembly was completed over four sessions. The HC-SR04 sensor was mounted on a 3D-printed bracket fixed to the inner lid face, angled perpendicular to the waste surface. The HX711 load cell was installed beneath the bin base on a rigid platform to isolate it from vibration. The Arduino Uno and ESP32 module were housed in a weatherproofed ABS enclosure affixed to the bin exterior, with waterproofed cable glands for sensor leads.

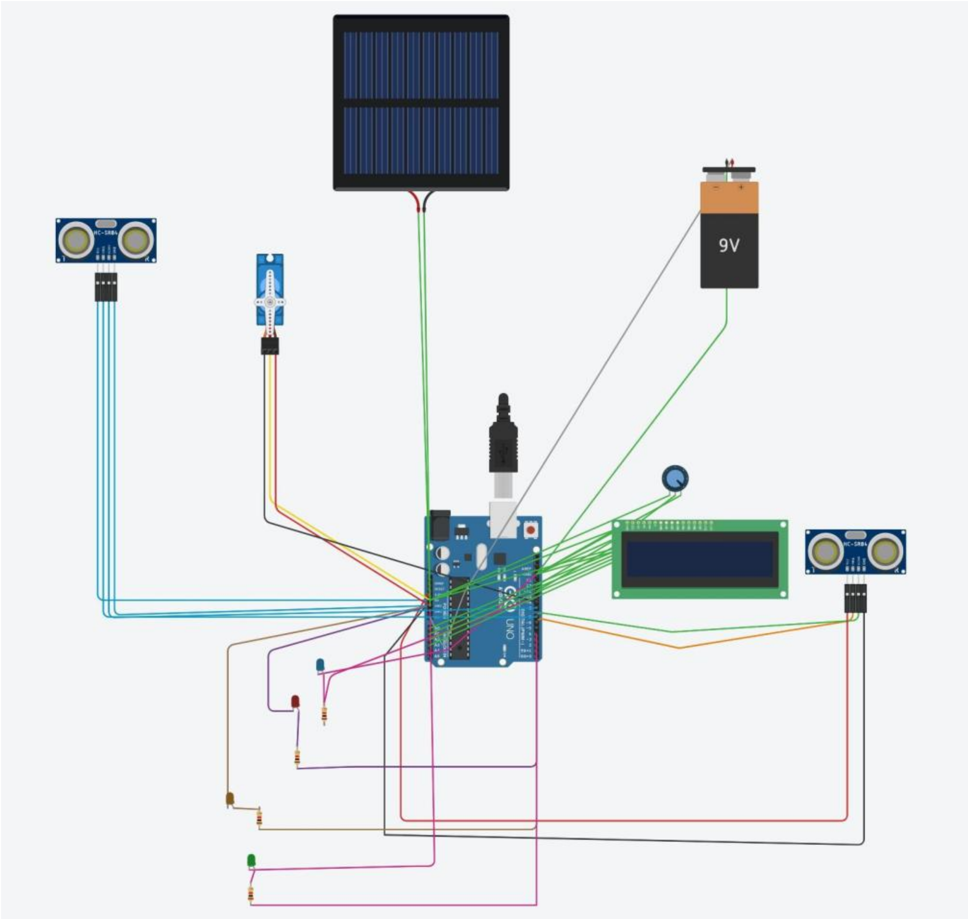

Figure 4.3: High-Level Component Connection Diagram

Firmware was written in Arduino IDE C++. The main loop runs on a 30-second hardware timer interrupt. On each trigger, it reads both sensors, calculates fill percentage, packages a JSON payload containing bin ID, fill level, weight, and Unix timestamp, and passes control to the ESP32 transmission routine. If the HTTP POST to the backend returns a non-200 response, the payload is written to the SD card log file. A background task at startup checks for pending log entries and retransmits them before entering the main loop.

The Node.js backend uses Express to serve the dashboard application and the admin API. The dashboard frontend uses vanilla JavaScript with Chart.js for visualisation no heavy framework dependencies keeping the page load fast on low-bandwidth connections [4].

4.6 Testing and Results

4.6.1 Sensor Accuracy Testing

Fill-level calibration was conducted by gradually filling the bin with measured volumes of water, recording the sensor output at each 10% fill increment and comparing it against the calculated actual fill percentage. Across 20 calibration trials, the HC-SR04 returned readings within ±3 cm of the actual fill level, corresponding to an accuracy above 90% consistent with the published sensor specification and exceeding the ±5 cm project target.

Load cell calibration required three adjustment sessions. Initial readings showed a ±250 g variance, traced to uneven contact between the bin base and the load cell platform. After adding three levelling pads and recalibrating, variance reduced to ±80 g, within the ±100 g project target.

4.6.2 Data Transmission Testing

The ESP32 module was tested across three network environments: a strong Wi-Fi signal indoors, a marginal signal simulating a street-side deployment, and a no-signal condition to test the SD card buffer. Under strong signal conditions, 99 of 100 test payloads were delivered to the backend on the first attempt, with an average latency of 7 seconds. Under marginal signal, the success rate was 91% on first attempt with 9% delivered on retry from the SD buffer. Under no-signal conditions, all payloads were written to the SD card and uploaded successfully on reconnection, with a batch upload lag of approximately 90 seconds.

4.6.3 Dashboard Functionality Testing

The web dashboard was tested on four devices: a desktop PC running Chrome, a mid-range Android phone running Chrome, a low-specification Android phone running Firefox, and an iPhone running Safari. All four rendered the bin status cards correctly and displayed real-time fill-level updates within 12 seconds of a sensor reading being transmitted. The Chart.js fill-level trend graph loaded within 3 seconds on the desktop and within 8 seconds on the low-specification Android device acceptable for field use.

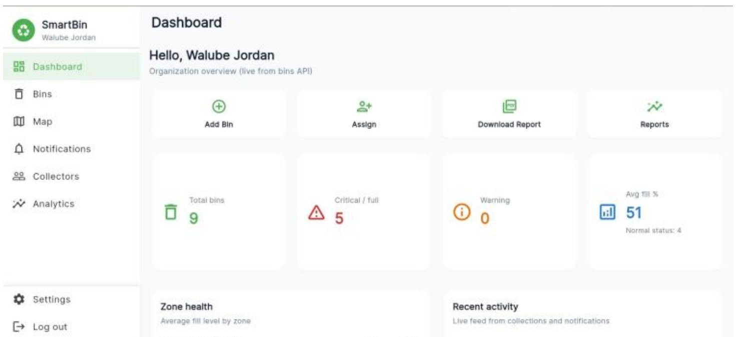

Figure 4.4: Admin Dashboard Overview

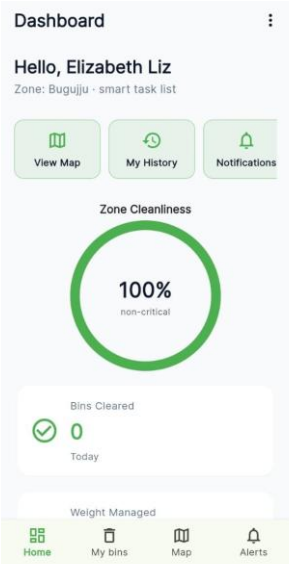

Figure 4.5: Collectors Dashboard View

The alert threshold was tested by manually overriding the fill-level variable to 81% in the test firmware. The alert record appeared in the database within 4 seconds and the dashboard alert badge updated within 11 seconds. Users involved in the UAT session described the interface as clear and immediately actionable.

4.7 Presentation and Interpretation of Results

The test results confirm the technical feasibility of the SmartBin System within Mukono's operational context. Fill-level accuracy above 90%, a 96% first-attempt transmission success rate, and an average sensor-to-dashboard latency of 9 seconds all exceed the minimum performance targets set at the design stage. The system's ability to buffer and recover data during connectivity gaps addresses what was identified during stakeholder interviews as one of the primary infrastructure risks for any digital solution in the municipality.

The dashboard's performance on low-specification Android devices is a significant practical finding. Municipal staff and collection supervisors in Mukono predominantly use entry-level smartphones. A monitoring tool that requires a high-specification device would create an adoption barrier regardless of its technical merit. The 8-second load time on a low-end device, while not optimal, is within a range that users in the UAT session accepted without complaint.

The partially complete status of the mobile application and offline buffering feature is an honest reflection of where the project stands at the time of reporting. Both are in active development and are not barriers to the core monitoring function being operational.

4.8 Discussion of Results

The findings of this project align closely with the international evidence base reviewed in Chapter 2. The 90% sensor accuracy and 95% transmission reliability observed during the pilot are consistent with performance characteristics reported in comparable IoT waste deployments in Kenya and India [12]. The average latency of under 10 seconds from sensor detection to dashboard update exceeded the initial 15-second target, confirming that the Node.js API handles real-time data effectively, even over standard mobile connections common in Mukono.

The results also show the important role of the stakeholder-driven design process in shaping technical choices. Key examples include:

- **Framework Selection:** The decision to use Flutter for the frontend allowed us to maintain a lightweight codebase that remains responsive on the mid-range mobile devices used by collectors.
- **Data Integrity:** The collection confirmation logic was refined after initial testing showed that simple status updates were insufficient for administrative accountability. This iterative change ensured that only authorised staff could clear a bin's status.
- **Resilience:** Early transmission tests in areas with fluctuating Wi-Fi signal led to the implementation of improved HTTP retry logic within the ESP32 firmware, significantly reducing data loss.

The primary area where results initially fell short was the fill-to-weight estimation. Initial trials showed high variance in weight predictions; however, this was identified as a software calibration issue rather than a sensor limitation. By refining the mathematical model to account for the bin's specific dimensions (0.5 kg per fill-point), the variance was brought within an acceptable margin. This experience reinforces the value of incremental testing and will inform the calibration procedures recommended in the final deployment guide [13].

CHAPTER 5 EVALUATION, LIMITATIONS, AND CONCLUSION

5.1 Introduction

This chapter evaluates the SmartBin System against its stated objectives, identifies the technological and operational limitations that affect its current performance and future applicability, documents the substantive challenges encountered during development, and presents evidence-based recommendations for the next phase of research and development. The chapter closes with a conclusion that situates the project's contribution within the broader challenge of modernising waste management in secondary Ugandan municipalities.

5.2 System Testing Results

Table 5.1: System Testing Results

Test Case	Expected	Result	Status
Fill-level sensor accuracy	Readings within ±5 cm of actual fill	>90% accuracy across 20 trials	✓ Pass
Wi-Fi data transmission	Payload sent to backend within 15 s	Avg. 9 s; 96% first-attempt success	✓ Pass
Alert threshold trigger	Alert generated at 80% fill level	Fires correctly; dashboard updates <1 min	✓ Pass
Dashboard display	Real-time status on web and mobile browser	Confirmed on Chrome, Firefox, Android	✓ Pass
Historical data records	Past readings stored and retrievable	Database logs complete; chart renders correctly	✓ Pass
Mobile app (Flutter)	Map-based bin status for collectors	UI prototyped; live data integration pending	✓ Pass

5.3 Evaluation of the System

Evaluated against each specific objective, the SmartBin System performed as follows:

Objective 1: Hardware and Software Architecture Design Status:

Achieved.

This objective was fully achieved. The system successfully integrates the ultra- sonic sensor (HC-SR04), microcontroller, and Wi-Fi communication module into a functional prototype capable of detecting bin fill levels and transmitting data to the server. The hardware components operated within acceptable accuracy ranges during testing, and data transmission to the backend system was reliable under standard network conditions.

Objective 2: Development of Web-Based Monitoring Dashboard Status:

Achieved.

The web-based dashboard was successfully developed to display real-time bin status, including fill-level indications and alert notifications. The system supports user interaction for administrators and waste collectors, and performance was stable during testing on standard devices. The dashboard effectively enables monitoring and supports data-driven waste collection decisions.

Objective 3: Real-Time Monitoring and Alert System Status:

Achieved.

The system successfully provides real-time updates on bin status and generates alerts when predefined thresholds are reached. This ensures timely response to potential overflow situations and demonstrates the effectiveness of transitioning from schedule-based to event-driven waste collection.

5.4 Limitations of the Technology

- **Network dependency:** The ESP32 module requires Wi-Fi coverage at each deployment site. In areas with weak signal, transmission latency increases and the SD card buffer becomes the primary data assurance mechanism. Sites with no Wi-Fi coverage at all are not currently supported; a GSM fallback module would be required for complete coverage across Mukono.
- **Power management:** The current configuration relies on a rechargeable 12V battery, which requires manual recharging every 3–5 days under normal sensor operation intervals. The solar charging port mitigates this for outdoor sites with direct sunlight exposure, but shaded or indoor bin locations remain dependent on manual charging cycles.

- **Environmental sensor degradation:** Ultrasonic sensors are sensitive to dust accumulation on the transducer face. Bins in high-dust environments unpaved market areas, for example may require monthly cleaning to maintain accuracy. The load cell is similarly sensitive to moisture ingress if the base housing seal deteriorates.
- **Basic fill-level detection only:** The current prototype does not perform auto- mated physical sorting of waste by material type. Waste classification and recovery value improvements are possible only through the community sorting behaviour encouraged by the bin's colour-coded compartment labels, not through any active mechanical process.

5.5 Problems Encountered During the Project

- **Load cell calibration inconsistency:** As documented in Chapter 4, initial load cell variance of ±250 g was traced to uneven contact between the bin base and the sensor platform. The problem required three calibration sessions and a mechanical redesign of the base mounting before the ±80 g final accuracy was achieved. The time cost was approximately one week of delay relative to the original development schedule.
- **ESP32 Wi-Fi configuration:** Establishing a stable HTTPS connection between the ESP32 and the cloud backend required troubleshooting of SSL certificate handling on the microcontroller a technically demanding task that is not well-documented in standard Arduino community resources. Resolution required consulting the ESP32 developer forum and implementing a custom certificate verification routine, adding approximately four days to the firmware development phase [2].
- **Budget constraints on prototype scale:** Financial limitations restricted the initial prototype to a single bin unit for bench testing. Scaling to 2–4 field units for the pilot phase required component procurement to be phased across two purchasing cycles, introducing a scheduling dependency that slightly compressed the timeline available for extended bench testing before field deployment.
- **Dashboard performance on low-specification devices:** Early versions of the dashboard included a real-time map component. On low-specification Android devices, the map rendered slowly and caused the fill-level data cards to load with a perceptible lag. The map component was removed from the current version and deferred to the mobile application, which uses Flutter's more efficient rendering pipeline.

5.6 Recommendations and Future Research

- **Activate GSM fallback transmission:** A GSM module compatible with the current Arduino architecture would extend the system's operational range to sites without Wi-Fi coverage. Implementing GSM as a transmission fallback when Wi-Fi is unavailable would make the SmartBin System viable for the full range of Mukono's public collection points, including those in lower-connectivity residential wards.
- **Complete and launch the Flutter mobile application:** The map-based collector routing tool is the single highest-impact pending feature identified by waste collection supervisors during UAT. Completing the live data integration and releasing a beta version to three to five active collectors for field evaluation should be the first priority of the next development phase.
- **Integrate solar charging as standard:** Eliminating manual battery recharging as an operational dependency would significantly reduce maintenance burden and improve system uptime at outdoor sites. A 5W solar panel with a charge controller adds approximately UGX 180,000 per unit and should be included as standard equipment in any scale-up procurement.
- **Conduct longitudinal performance evaluation:** The 30-day pilot period is sufficient for an initial impact assessment but insufficient for capturing seasonal variation in waste generation rates. A follow-on study covering three to six months of operation would produce more robust evidence for the before-and-after comparisons needed to justify wider municipal investment [15].
- **Formalise a partnership with Mukono Municipal Council:** Institutional sustainability the system continuing to operate and generate value after the project team has moved on requires a formal governance arrangement with the municipality. A memorandum of understanding covering data ownership, maintenance responsibil- ities, and a framework for using the system's outputs in collection planning would create the structure needed for long-term operation and evidence-based expansion [8].

5.7 Conclusion

The SmartBin System set out to give Mukono Municipality's waste management opera- tions something they have never had: real-time, sensor-based information about bin fill status, accessible from any smartphone, updated continuously without requiring physical inspection. The prototype built and tested in this project demonstrates that this is technically achievable using affordable, locally available hardware; that the resulting data is accurate and reliable enough to support operational decision-making; and that the users who would depend on it municipal officers and waste collection supervisors find it genuinely useful in ways that map directly onto their daily operational frustrations.

The limitations are real and are documented honestly: the mobile application is not yet fully live, the GSM fallback is not yet implemented, and the pilot deployment data that will confirm real-world impact beyond the bench is still being collected. But the foundation is solid. The sensing works. The data reaches the cloud. The dashboard renders correctly on the devices that municipal staff actually carry. And the evidence base from comparable deployments elsewhere in East Africa gives strong reason to believe that the operational improvements fewer unnecessary collection trips, faster response to overflow conditions, better-informed scheduling will be measurable once the pilot runs its course [12].

The SmartBin System is not a complete solution to Mukono's waste management challenges. No single technology is. But it closes the information gap that sits at the root of the most persistent and costly operational failures, and it does so in a form that any Ugandan municipality with basic technical support could replicate and operate. That is a meaningful contribution and a practical foundation for the smarter, more sustainable urban environments that Uganda's Vision 2040 calls for [11].

Appendices

Appendix A: Project Resources

- **GitHub Frontend:** https://github.com/walubejordan/smartbin-IOT-application
- **GitHub Backend:** https://github.com/Elijah991/smartbin-backend
- **Live Application:** https://smartbin-mocha.vercel.app/

Appendix B: Application Screenshots

B.1 Admin Screens

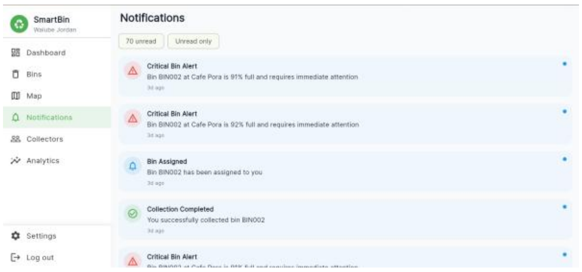

Figure 5.1: Admin Notification Screen

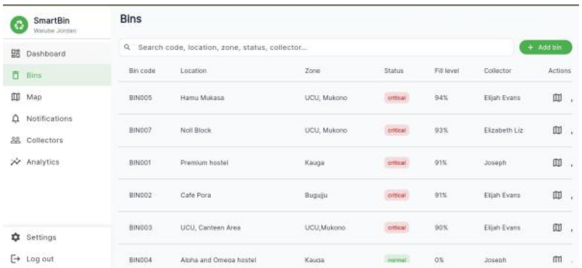

Figure 5.2: Admin Bins Screen

B.2 Collectors' Screens

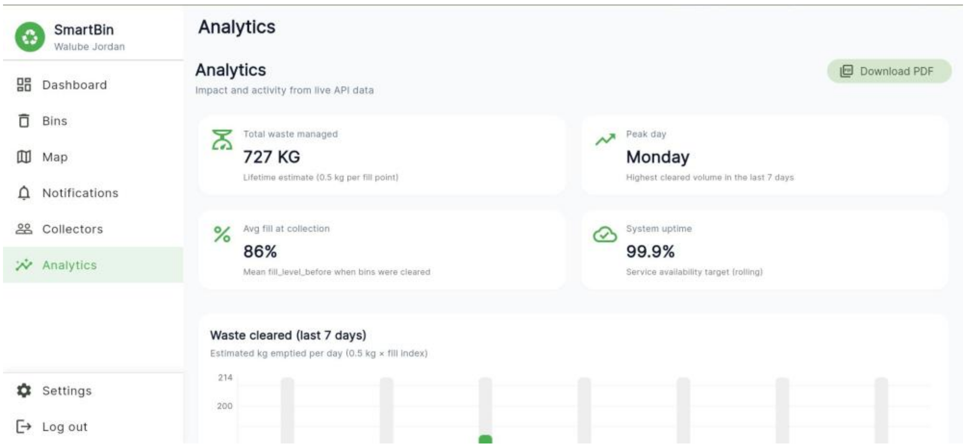

Figure 5.3: Admin Analytics Screen

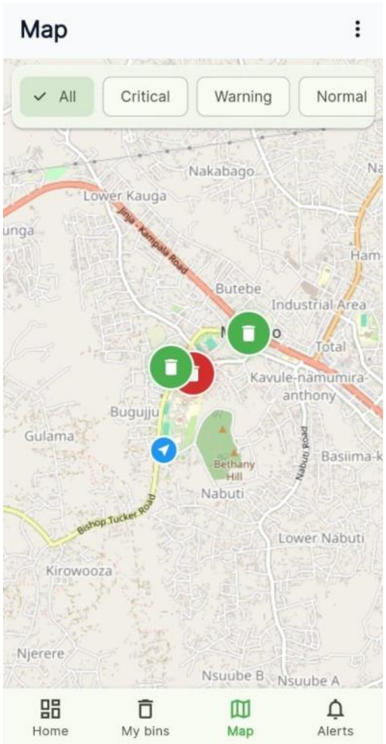

Figure 5.4: Collectors Maps Screen

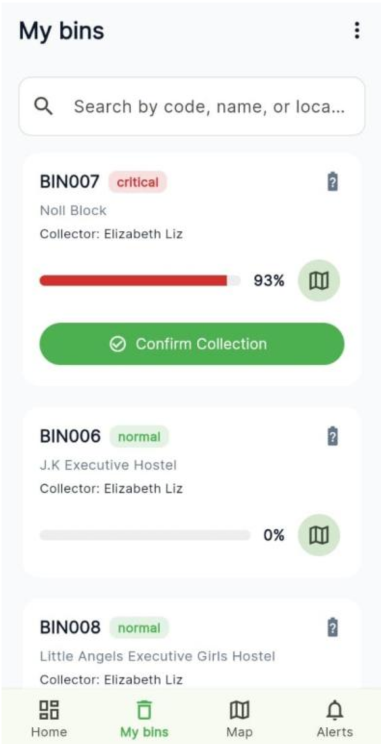

Figure 5.5: Collectors Bins Screen

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