

Smart Waste Management System

R26-IT-126

Project Proposal Report(Draft)

B.Sc.(Hons) Degree in Information technology specialized in Information
Technology

Department of Information Technology Sri Lanka

Institute of Information Technology

March 2026

IoT-Based Environmental Sensing Smart Bin

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DECLARATION

I declare that this is my own work, and this proposal does not knowingly incorporate any material previously submitted for a degree or diploma at any other university or higher education institution, nor does it contain any material that has been previously published or written by another person apart from where proper acknowledgment is given in the text.

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ABSTRACT

Rapid urbanization and the exponential growth of waste generation have exposed critical limitations in conventional waste management systems, which continue to rely on fixed-route collection schedules that are inherently reactive and operationally inefficient. These systems lack real-time insight into bin conditions, resulting in overflows, unnecessary collection trips, elevated labor and fuel costs, and significant environmental hazards.

This research addresses the identified knowledge gap by designing, developing, and implementing an Environmental Sensing Smart Bin a hardware-firmware-cloud integrated unit that continuously monitors multiple waste bin parameters in real time. The proposed system leverages an ESP32 microcontroller interfaced with a suite of sensors: an HC-SR04 ultrasonic sensor for fill-level detection, a load cell with HX711 amplifier for weight measurement, MQ-135 and MQ-4 gas sensors for hazardous gas concentration monitoring, and a DHT22 sensor for ambient temperature and humidity acquisition. Sensor data is preprocessed via embedded Arduino firmware, structured in JSON format, and transmitted to cloud platforms (Microsoft Azure / Firebase) over Wi-Fi using MQTT/HTTP protocols.

A color-coded status alerting system (GREEN, YELLOW, RED) provides operational personnel with immediate, actionable insights into bin criticality. The system's novelty lies in its multi-parameter environmental fusion approach, which extends beyond conventional fill-level monitoring to incorporate gas emissions and thermal-environmental context, enabling early hazard detection and richer data collection for downstream machine learning modules operating at the group system level.

The expected outcomes include a validated, cloud-connected smart bin prototype with calibrated sensor accuracy, real-time telemetry to the cloud, wiring documentation, and sample data charts. The system directly contributes to UN Sustainable Development Goals (SDGs) 11 (Sustainable Cities), 12 (Responsible Consumption), and 13 (Climate Action), while providing strong commercialization potential for municipal operators and private waste management companies.

Keywords: IoT Smart Bin, ESP32, Environmental Sensing, Multi-Parameter Monitoring, Cloud Telemetry, Waste Management, Gas Detection, Real-Time Alerting

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Gratitude is also extended to the academic staff of the Department of Information Technology, SLIIT, for providing the foundational knowledge in IoT systems, embedded firmware development, and cloud computing that underpins this research.

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LIST OF ABBREVIATIONS

Abbreviation	Full Form
IoT	Internet of Things
ESP32	Espressif Systems 32-bit Wi-Fi + Bluetooth Microcontroller
MQTT	Message Queuing Telemetry Transport
HTTP	Hypertext Transfer Protocol
JSON	JavaScript Object Notation
DHT22	Digital Humidity and Temperature Sensor (Model 22)
MQ-135	Air Quality / Ammonia / NOx Gas Sensor
MQ-4	Methane / Natural Gas Sensor
HC-SR04	Ultrasonic Distance Sensor
HX711	24-bit ADC Amplifier for Load Cell
ADC	Analog-to-Digital Converter
GPIO	General-Purpose Input/Output
SDK	Software Development Kit
SDG	Sustainable Development Goal
ML	Machine Learning
API	Application Programming Interface
SLIIT	Sri Lanka Institute of Information Technology
WBS	Work Breakdown Structure
ppm	Parts Per Million
%RH	Percentage Relative Humidity

CHAPTER 1: INTRODUCTION

1.1 Background and Context

Waste management constitutes one of the most pressing sustainability challenges confronting urban administrations worldwide. According to the World Bank, global solid waste generation is projected to reach 3.4 billion tonnes annually by 2050, representing a 70% increase from 2016 levels, with the steepest growth trajectories occurring in rapidly urbanizing regions of South Asia and Sub-Saharan Africa [1]. In the Sri Lankan context, the Colombo Municipal Council (CMC) alone generates approximately 800 tonnes of municipal solid waste (MSW) per day, with current collection and disposal infrastructure operating well below the threshold required for effective management [2].

Conventional waste collection systems are characterized by a reactive operational paradigm: collection vehicles follow predetermined schedules and fixed routes irrespective of actual bin fill conditions. This leads to a range of documented inefficiencies including premature collections of partially filled bins, delayed service for critically overflowing bins, increased fuel consumption, excessive labor allocation, and preventable environmental contamination. Research by Anagnostopoulos et al. (2015) demonstrated that dynamic, sensor-informed routing can reduce operational costs by up to 40% compared to static scheduling approaches [3].

The proliferation of low-cost IoT sensor platforms - particularly ESP32-class microcontrollers with integrated Wi-Fi and Bluetooth capabilities - and the maturation of cloud platforms such as Microsoft Azure IoT Hub and Google Firebase have created a viable technological foundation for intelligent, data-driven waste management systems. However, the deployment of truly comprehensive smart bin solutions remains limited, with most commercially available products focusing exclusively on ultrasonic fill-level sensing without capturing the richer environmental context that would enable early hazard detection and more sophisticated waste composition prediction.

This research is explicitly aligned with United Nations Sustainable Development Goals: SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) [4]. It is further aligned with SLIIT's research cluster in Intelligent and Pervasive Computing Systems, contributing to the broader group project's objective of building an end-to-end predictive waste management framework.

1.2 Literature Review

1.2.1 IoT-Enabled Smart Bin Systems

The foundational work in IoT-based waste management was pioneered by Mamun et al. (2016), who demonstrated the viability of ultrasonic-based fill-level monitoring with GSM communication for bin status reporting. Their system achieved an average measurement accuracy of 94.7% in outdoor deployment conditions, establishing the technical feasibility of automated bin monitoring. However, this early work lacked multi-parameter sensing, cloud integration, and any form of predictive analytics [5].

Sridhar et al. (2018) extended this framework by incorporating microcontroller-based embedded systems with multiple communication protocols, demonstrating that ESP8266 and ESP32-class devices offered a compelling cost-performance trade-off for IoT edge devices in waste management applications. Their work highlighted the critical importance of firmware optimization for low-power operation in field-deployed units [6].

A comprehensive survey by Kumar and Patel (2020) identified that while fill-level monitoring is the most widely implemented IoT feature in smart bins, the integration of environmental sensors (gas, temperature, humidity) represents a significant research gap with substantial practical value, particularly in contexts where organic waste decomposition generates hazardous gas emissions [7].

1.1.1 Gas and Environmental Monitoring in Waste Management

The decomposition of organic waste in bins generates a complex mixture of gases including methane (CH₄), hydrogen sulfide (H₂S), ammonia (NH₃), and carbon dioxide (CO₂). Concentrations of methane above 5% and hydrogen sulfide above 10 ppm represent direct hazard thresholds for sanitation workers and surrounding communities [8]. Existing research by Pardini et al. (2020) established that MQ-series gas sensors, despite their limitations in precise quantitative measurement, provide effective binary and threshold-based alerting suitable for operational waste management contexts at substantially lower cost than industrial-grade electrochemical sensors [9].

Notably, the integration of gas sensing with fill-level and weight data enables a new dimension of hazard correlation analysis for instance, a bin that is only 50% full but exhibiting elevated methane concentrations may warrant priority collection due to unsafe decomposition rates, a decision that

fill-level monitoring alone cannot support. This multi-parameter fusion approach is a core innovation of the proposed system.

1.2.2 Load Cell and Weight Measurement in Smart Bins

Weight measurement provides complementary information to volumetric fill-level sensing, particularly relevant for heterogeneous waste streams where material density varies significantly. Chang et al. (2019) demonstrated that combining volumetric and gravimetric measurements improves waste composition estimation accuracy by 23% compared to volumetric sensing alone, providing valuable input features for downstream machine learning classification models [10]. The HX711 precision analog-to-digital converter, designed specifically for load cell amplification, provides 24-bit resolution suitable for detecting weight changes of under 10 grams in field conditions.

1.2.3 ESP32 as an IoT Edge Platform

The Espressif ESP32 has emerged as a dominant platform for IoT edge computing due to its dual-core 240 MHz Xtensa LX6 processor, integrated 802.11b/g/n Wi-Fi, Bluetooth 4.2, rich GPIO peripheral interface, and sub-USD 5 unit cost. Extensive research by Maier et al. (2017)

benchmarked ESP32 against competing microcontroller platforms (Arduino Mega, Raspberry Pi Zero) and concluded that ESP32 offers the optimal balance of processing power, connectivity, power consumption, and cost for IoT sensor aggregation applications [11].

For the proposed environmental sensing smart bin, ESP32's ability to simultaneously manage multiple sensor interfaces (UART, I2C, SPI, ADC, digital GPIO) while maintaining persistent Wi-Fi connectivity for MQTT/HTTP cloud transmission makes it the technology of choice.

1.2.4 Cloud Platforms for IoT Telemetry

Microsoft Azure IoT Hub and Google Firebase Realtime Database represent the two primary cloud platforms evaluated for this research. Azure IoT Hub provides enterprise-grade device management, bi-directional messaging, and integration with Azure Stream Analytics and Azure Machine Learning services, making it the preferred choice for large-scale commercial deployments [12]. Firebase offers simpler integration, real-time synchronization, and a generous free tier suitable for prototyping and academic deployment [13]. This research targets Firebase for

initial prototype development with a documented migration pathway to Azure IoT Hub for production-scale deployment.

1.2.5 Comparison of Existing Smart Bin Products and Systems

A comparative analysis of commercially available and research-documented smart bin solutions reveals the following landscape:

System / Product	Fill Level	Weight	Gas Sensing	Env. Monitoring
Bigbelly Smart Bin	Yes	No	No	No
Ecube Labs CanSolve	Yes	No	No	No
Mamun et al. (2016)	Yes	No	No	No
Sridhar et al. (2018)	Yes	No	No	No
Pardini et al. (2020)	Yes	No	Yes (CH ₄)	Partial
PROPOSED SYSTEM	Yes	Yes	Yes (MQ-135, MQ-4)	Yes (DHT22)

TABLE 1 COMPARISON OF EXISTING BIN PRODUCTS

As the comparative analysis demonstrates, no existing commercial or research system integrates the complete suite of fill level, weight, gas concentration, and ambient environmental monitoring within a single, cloud-connected embedded unit. This multi-parameter integration represents the core technical novelty of the proposed Environmental Sensing Smart Bin.

1.3 Research Gap

Critical Gap: Existing smart bin systems predominantly focus on single-parameter fill-level monitoring, failing to capture the multi-dimensional environmental context needed for early hazard detection, accurate waste composition estimation, and genuinely proactive waste management operations.

The specific research gaps addressed by this study are:

- Absence of integrated multi-parameter IoT sensing: No existing smart bin solution simultaneously monitors fill level, weight, gas concentrations, and ambient environmental conditions within a single coherent hardware-firmware system.
- Limited hazard detection capability: Current systems cannot detect dangerous gas accumulations that pose occupational health risks to sanitation workers or environmental hazards to surrounding communities before bin overflow.
- Insufficient data richness for ML-based composition prediction: Single-parameter fill-level data provides inadequate feature richness for accurate waste composition forecasting; multi-parameter sensing creates a substantially richer training dataset.
- Lack of cloud-integrated edge-to-cloud telemetry with structured data formatting: Most research prototypes lack production-quality data pipelines with JSON-structured, timestamped telemetry suitable for cloud storage and ML model training.

Addressing these gaps will contribute both to the immediate practical goal of proactive waste management and to the longer-term academic goal of establishing a validated, multi-parameter IoT dataset for waste management research.

CHAPTER 2: OBJECTIVES

2.1 Main Objective

To design, develop, and implement a multi-parameter Environmental Sensing Smart Bin that continuously and reliably monitors waste fill level, weight, gaseous emissions, and ambient environmental conditions using an ESP32-based embedded system, transmitting structured real-time telemetry to a cloud platform to enable intelligent, proactive, and data-driven waste management operations

2.2 Specific Objectives

The following specific, measurable objectives have been defined for this individual component:

1. To design and implement a sensor-integrated hardware system architecture for the environmental sensing smart bin utilizing the ESP32 microcontroller with HC-SR04 (ultrasonic fill level), load cell + HX711 (weight), MQ-135 (air quality / ammonia / CO2), MQ-4 (methane), and DHT22 (temperature / humidity) sensors.
2. To develop embedded firmware in Arduino/C++ for sensor data acquisition, unit conversion (cm, kg, ppm, °C, %RH), threshold-based criticality classification (GREEN / YELLOW / RED), and structured JSON data formatting for cloud transmission.
3. To implement reliable cloud connectivity via MQTT/HTTP over Wi-Fi, transmitting timestamped, multi-parameter JSON telemetry payloads to Firebase Realtime Database (prototype) / Microsoft Azure IoT Hub (production).
4. To design and implement a real-time color-coded alert mechanism (GREEN: normal operation, YELLOW: advisory warning, RED: critical action required) based on configurable multi-parameter thresholds for fill level, gas concentrations, and weight.
5. To conduct systematic sensor calibration, validation testing across diverse operational conditions (indoor, outdoor, varying waste types), and quantitative performance assessment against defined accuracy and reliability metrics.
6. To analyze and document collected sensor data, producing wiring diagrams, calibration records, sample data charts, and a validated dataset suitable for downstream integration with the group's ML-based waste composition prediction and route optimization modules.

2.3 Alignment with Group Project Objectives

This individual component directly enables the broader group project's goal of building an end-to-end intelligent waste management framework. The multi-parameter telemetry generated by this component serves as the primary data source for three inter-dependent group components:

Group Component	Dependency on This Component
Fill-Level Monitoring & Occupancy Detection (IT22202772)	Receives validated fill-level sensor data streams

ML Waste Composition Prediction (IT22213358)	Requires multi-parameter sensor data (weight, gas, temp/humidity) for feature engineering
Dynamic Route Optimization (IT22088482)	Depends on real-time bin criticality status (GREEN/YELLOW/RED) for routing decisions
This Component (IT22548528)	Provides foundational sensing infrastructure for all other components

CHAPTER 3: METHODOLOGY

3.1 Research Approach

This research adopts a Design Science Research (DSR) methodology, which is appropriate for applied engineering research that aims to create, build, and evaluate IT artifacts [14]. DSR provides a structured framework for iterative prototype development, empirical evaluation, and contribution to both practice and knowledge. The research proceeds through three primary phases:

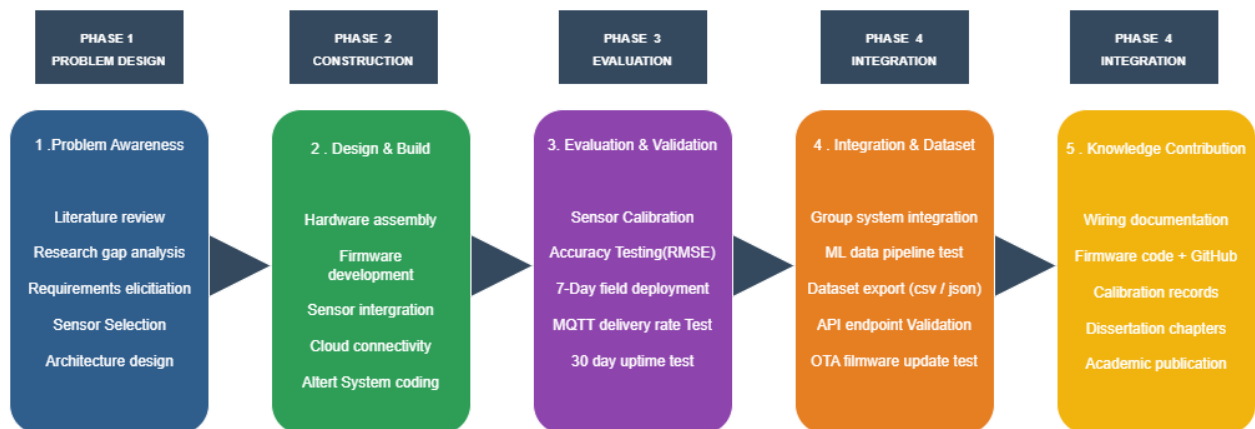


FIGURE 1 : DESIGN SCIENCE RESEARCH METHODOLOGY

- Phase 1 – Problem Awareness : Identification of the research problem through literature review, stakeholder analysis, and requirement elicitation.
- Phase 2 – Design and Build : Development of the hardware and firmware architecture including sensor integration, ESP32 programming, and cloud connectivity.
- Phase 3 – Evaluation and Validation : Calibration of sensors, accuracy testing, field deployment experiments, and system performance evaluation.
- Phase 4 – Integration and Dataset Generation : Integration with cloud platforms, API validation, and generation of structured datasets for downstream analytics.
- Phase 5 – Knowledge Contribution : Documentation of system design, firmware code, calibration results, and research findings contributing to academic and practical knowledge.

3.2 Hardware Design Methodology

3.2.1 Sensor Selection Rationale

The sensor suite was selected based on a systematic evaluation matrix considering measurement accuracy, operational cost, physical compatibility with waste bin deployment, supply chain availability in Sri Lanka, and community/library support for ESP32 integration.

Sensor	Parameter Measured	Key Specification	Selection Rationale
HC-SR04	Fill Level (Distance)	2–400 cm, ± 3 mm accuracy	Low cost, proven accuracy, ESP32 compatible
Load Cell + HX711	Waste Weight	0–50 kg, 24-bit ADC	Gravimetric complement to volumetric fill
MQ-135	NH ₃ , CO ₂ , Benzene, Air Quality	10–300 ppm, fast response	Detects organic decomposition gases

MQ-4	Methane (CH ₄)	200–9,999 ppm	Dedicated methane / biogas detection
DHT22	Temperature & Humidity	-40 to +80°C, ±0.5°C; 0–100% RH, ±2%	Environmental context for gas normalization

TABLE 2 : SENSOR SELECTION RETIONALE

3.2.2 Physical Mounting and Enclosure Design

The sensors are positioned within the bin assembly to maximize measurement fidelity and physical durability:

- HC-SR04 (Ultrasonic): Mounted facing downward on the interior of the bin lid, centered, providing direct line-of-sight measurement to waste surface.
- Load Cell (Weight): Positioned at the bin base beneath a fixed internal platform, isolated from lateral forces using corner mounting brackets.
- MQ-135 and MQ-4 (Gas): Mounted near the top interior sidewall to intercept rising gas concentrations; protected by perforated acrylic shields against direct liquid contact.
- DHT22 (Temperature/Humidity): Mounted on the underside of the lid, shielded from direct rain and solar radiation, positioned in the ambient air column above the waste surface.
- ESP32 + HX711: Housed in a sealed, IP54-rated weatherproof enclosure attached to the bin exterior wall, with cable glands for sensor wire entry.

All sensor positions will be documented with dimensioned wiring diagrams created in Fritzing and KiCad, forming part of the technical deliverables.

3.3 Firmware Development Methodology

3.3.1 Development Environment and Tools

Tool / Platform	Purpose
-----------------	---------

Arduino IDE 2.x	Primary firmware development environment
ESP32 Arduino Core (Espressif)	HAL and peripheral libraries for ESP32
PlatformIO (VS Code extension)	Dependency management and CI build
NewPing Library	HC-SR04 ultrasonic sensor abstraction
HX711 Library (bogde)	Load cell amplifier data reading
DHT Sensor Library (Adafruit)	DHT22 temperature/humidity acquisition
ArduinoJson	JSON serialization and deserialization
PubSubClient	MQTT protocol implementation for ESP32
Firebase ESP Client	Firebase Realtime Database integration
Git / GitHub	Version control and code documentation

TABLE 3 : DEVELOPMENT ENVIROMENT AND TOOLS

3.3.2 Firmware Architecture

The firmware is structured as a modular, task-oriented system organized into the following functional layers:

1. Sensor Abstraction Layer: Encapsulates raw sensor I/O; each sensor has a dedicated module with initialization, read, calibrate, and status functions.
2. Data Processing Layer: Applies moving average filtering, unit conversion, and offset calibration to raw sensor readings.
3. Threshold Classification Layer: Evaluates processed readings against configurable threshold tables to determine the bin's criticality status (GREEN / YELLOW / RED).
4. Serialization Layer: Constructs a structured JSON payload with all sensor readings, timestamp, bin ID, GPS coordinates, and criticality status.

5. Communication Layer: Manages Wi-Fi connection, MQTT broker connection, and HTTP/MQTT message dispatch to the cloud endpoint.
6. Watchdog and Recovery Layer: Implements ESP32 hardware watchdog, automated Wi-Fi reconnection, and graceful error handling to ensure 24/7 unattended operation.

3.3.3 Alert Threshold Design

The color-coded status system uses a multi-dimensional threshold matrix evaluated against all sensor parameters simultaneously:

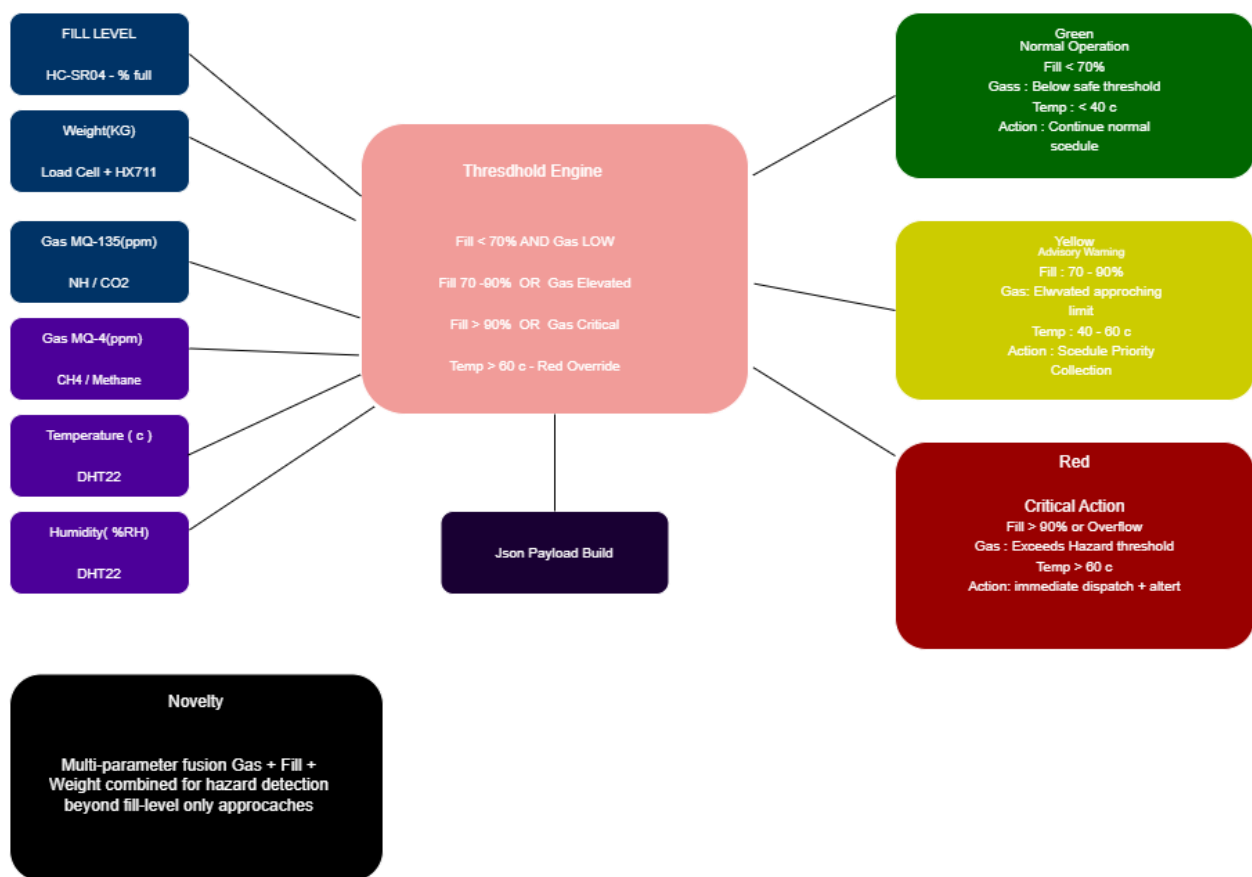


FIGURE 2 ALERT THRESHOLD DESIGN

Status	Fill Level	Gas Concentration (MQ-135 / MQ-4)	Temperature
GREEN (Normal)	< 70%	Below safe operational thresholds	< 45°C
YELLOW (Warning)	70–90%	Elevated: approaching hazard threshold	45–60°C
RED (Critical)	> 90% or overflow	Exceeds hazard threshold	> 60°C

Threshold values will be finalized through empirical calibration testing and aligned with published occupational health guidelines for gas concentrations.

3.4 Cloud Integration Methodology

3.4.1 Data Transmission Protocol

Data transmission follows a structured pipeline: the ESP32 sends JSON payloads to Firebase Realtime Database via HTTP REST API (prototype phase) and to Azure IoT Hub via MQTT with TLS 1.2 encryption (production phase). The payload structure is defined as follows:

```
{ "bin_id": "BIN_001", "timestamp": "2024-08-15T10:30:00Z", "location": { "lat": 6.9271, "lon": 79.8612 }, "fill_level_pct": 67.3, "weight_kg": 12.4, "gas_mq135_ppm": 145, "gas_mq4_ppm": 210, "temperature_c": 32.1, "humidity_rh": 74.5, "status": "GREEN" }
```

Data is transmitted every 60 seconds under normal operation, with immediate transmission triggered on any status transition (GREEN > YELLOW or YELLOW > RED).

3.5 Calibration and Validation Methodology

3.5.1 Calibration Protocol

Each sensor will undergo a structured calibration procedure prior to field deployment:

- HC-SR04: Calibrated against a reference steel ruler across the full operational range (0–100 cm) at 5 cm intervals; offset and gain correction applied in firmware.

- Load Cell + HX711: Calibrated using certified reference weights (100 g, 500 g, 1 kg, 5 kg, 10 kg, 20 kg); tare function implemented for bin self-weight compensation.
- MQ-135 / MQ-4: Burn-in procedure (48 hours at 5V) followed by clean-air baseline calibration and cross-validation using reference gas mixtures where available; Rs/R0 ratio calibration applied.

DHT22: Validated against a certified reference thermometer-hygrometer; no calibration correction required if within factory specification

3.5.2 Performance Evaluation Metrics

Metric	Target Value
Fill Level Measurement Accuracy	±5% of true value across operational range
Weight Measurement Accuracy	±200 g across 0–50 kg range
Gas Alert Trigger Accuracy	> 95% true positive rate at defined thresholds
System Uptime (MTBF)	> 720 hours continuous operation without manual restart
Cloud Transmission Latency	< 5 seconds from sensor reading to cloud record
JSON Payload Delivery Rate	> 99% successful transmission rate over 7-day test period

TABLE 4 : PERFORMANCE EVALUATION METRICS

3.6 Data Collection and Ethical Considerations

Data collection for this research involves IoT sensor measurements from deployed physical bins and does not involve human subjects, personally identifiable information, or privacy-sensitive data. The following ethical considerations are noted:

- **Location Data:** GPS coordinates transmitted as part of the bin telemetry represent the fixed location of municipal property and are not privacy-sensitive.
- **Environmental Data:** All sensor readings represent physical environmental parameters of waste bins in public or institutional spaces.
- **Data Security:** Cloud platforms employ TLS encryption for data in transit; Firebase authentication and Azure SAS tokens provide access control for data at rest.
- **Data Retention:** Research data will be retained for a minimum of 3 years in accordance with SLIIT research data management guidelines.

CHAPTER 4: HIGH-LEVEL SYSTEM ARCHITECTURE

4.1 Overall Group System Architecture Overview

The complete group system is organized as a four-layer cloud-centric architecture:

- **Edge Layer:** Environmental Sensing Smart Bins (this component) and Smart Fill-Level Monitoring Units collect multi-parameter sensor data and transmit to cloud.
- **Cloud Data Layer:** Microsoft Azure IoT Hub / Firebase Realtime Database consolidates bin telemetry with auxiliary data sources (Weather APIs, Calendar APIs, historical collection records, zone boundary data).
- **Analytics Layer:** ML modules for waste composition prediction and predictive analytics engine process consolidated data to generate forecasts and bin criticality assessments.
- **Decision and Action Layer:** Optimized collection routes generated and dispatched to vehicle operators and recycling facilities.

4.2 Individual Component Architecture: Environmental Sensing Smart Bin

4.2.1 Hardware Layer

The hardware layer consists of the physical bin unit with the following primary components and their interconnections:

Component	Interface with ESP32
HC-SR04 Ultrasonic Sensor	Digital GPIO (Trigger: GPIO 5, Echo: GPIO 18)
Load Cell + HX711	SPI-like 2-wire interface (DT: GPIO 21, SCK: GPIO 22)
MQ-135 Gas Sensor	ADC (GPIO 34) + Digital threshold output (GPIO 35)
MQ-4 Gas Sensor	ADC (GPIO 36) + Digital threshold output (GPIO 39)
DHT22 Sensor	Single-wire digital protocol (GPIO 4)
Status LED (RGB)	PWM GPIO (R: GPIO 25, G: GPIO 26, B: GPIO 27)
Power Supply	3.3V / 5V regulated from 12V Li-ion battery or mains adapter

TABLE 5 : PRIMARY COMPONENTS OF HARDWARE LAYER

4.2.2 Firmware Layer

The firmware layer implements the sensor read cycle, data processing pipeline, threshold evaluation, and cloud communication. The main execution loop operates on a 60-second polling interval with interrupt-driven override for threshold breach events. The firmware is compiled and flashed via USB-C UART bootloader, with OTA (Over-The-Air) firmware update capability implemented for post-deployment maintenance.

4.2.3 Communication Layer

Communication follows a two-tier approach: local data buffering in ESP32 SPIFFS filesystem for up to 24 hours of readings during Wi-Fi outages, with automatic retry and batch upload upon

connectivity restoration; and real-time MQTT publication for live operations. This ensures data continuity even in intermittent network environments typical of outdoor urban deployments

4.2.4 Cloud Layer

Firebase Realtime Database is organized with the following data hierarchy:

/bins/{bin_id}/current → Most recent sensor reading /bins/{bin_id}/history/{timestamp} → Historical readings /bins/{bin_id}/alerts/{alert_id} → Status transition events /config/{bin_id}/thresholds → Configurable alert thresholds.

4.3 Data Flow Description

The end-to-end data flow proceeds through the following sequential stages:

1. **Sensor Acquisition:** ESP32 polls all five sensor inputs on the 60-second cycle. Raw ADC values, digital pulse widths, and digital protocol responses are read.
2. **Signal Processing:** Raw values are passed through moving average filters (window = 5 samples) and calibration correction functions to produce physically meaningful values with appropriate units.
3. **Threshold Evaluation:** Processed values are evaluated against the multi-parameter threshold matrix to determine the bin's current status (GREEN / YELLOW / RED). RGB LED is updated to reflect status.
4. **JSON Serialization:** ArduinoJson constructs a structured JSON payload including all sensor values, computed status, bin ID, timestamp (from NTP), and GPS coordinates.
5. **MQTT/HTTP Transmission:** PubSubClient publishes the JSON payload to the Firebase MQTT endpoint. Failed transmissions are queued in SPIFFS for subsequent retry.
6. **Cloud Storage:** Firebase stores the received payload in the Realtime Database under the appropriate bin's hierarchy, triggering cloud functions for alert notifications if status is RED.

7. Downstream Consumption: Group ML components read current and historical data from Firebase to generate composition predictions and criticality assessments for route optimization.

4.4 Scalability and Security Considerations

The architecture is designed to scale from a single-bin prototype to a city-wide deployment of thousands of bins:

- Device Management: Each bin carries a unique bin_id provisioned at firmware flash time; Azure IoT Hub supports fleet management of millions of devices.
- Data Volume: At one reading per 60 seconds per bin, 1,000 bins generate approximately 1.44 million records per day, well within Firebase and Azure IoT Hub capacity tiers.
- Security: TLS 1.2 encryption for all cloud communications; MQTT authentication using pre-shared keys; Firebase Security Rules restrict read/write access by authenticated service accounts only.
- Maintainability: OTA firmware update capability eliminates the need for physical access for software maintenance; remote threshold configuration via cloud-to-device MQTT messaging.

CHAPTER 5: USER REQUIREMENTS

5.1 Stakeholder Identification

Stakeholder	Relationship to System
Municipal Solid Waste Operators (CMC / Local Authorities)	Primary operational users; receive bin status alerts and telemetry
Private Waste Collection Companies	Commercial operators integrating bin data with fleet management
Sanitation Field Workers / Truck Drivers	End beneficiaries of alert system; receive collection dispatches
Environmental Health Officers	Monitor gas concentration data for occupational safety compliance
City Planners and Sustainability Officers	Access aggregated analytics for strategic waste infrastructure planning
Downstream ML Research Components (Group Members)	Technical consumers of raw sensor data streams
SLIIT Academic Supervisors	Research oversight and evaluation

TABLE 6 : STAKEHOLDER IDENTIFICATION

5.2 Functional Requirements

The following functional requirements have been elicited through stakeholder analysis and research objectives:

FR ID	Requirement Description	Priority	Source
FR-01	The system shall measure bin fill level using ultrasonic sensing with accuracy within $\pm 5\%$ of true fill percentage.	High	Stakeholder / LO
FR-02	The system shall measure waste weight using a calibrated load cell with accuracy within $\pm 200\text{g}$.	High	Stakeholder / LO
FR-03	The system shall monitor gas concentrations (NH ₃ , CO ₂ via MQ-135; CH ₄ via MQ-4) in ppm units.	High	Safety / LO
FR-04	The system shall monitor ambient temperature ($^{\circ}\text{C}$) and relative humidity (%RH) via DHT22.	Medium	Context / LO
FR-05	The system shall classify bin status as GREEN, YELLOW, or RED based on multi-parameter threshold evaluation.	High	Operational
FR-06	The system shall transmit structured JSON telemetry to cloud every 60 seconds.	High	Data Pipeline
FR-07	The system shall trigger immediate cloud transmission on any status transition.	High	Alerting
FR-08	The system shall buffer data locally for up to 24 hours during network outages.	Medium	Reliability
FR-09	The system shall support OTA firmware updates via Wi-Fi.	Medium	Maintainability
FR-10	The system shall operate continuously for a minimum of 720 hours without manual restart.	High	Reliability
FR-11	The system shall produce RGB LED visual status indication at the bin.	Low	Usability

FR-12	The system shall support remote threshold reconfiguration via cloud-to-device messaging.	Medium	Flexibility
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TABLE 7 : FUNCTIONAL REQUIREMENTS

5.3 Non-Functional Requirements

NFR ID / Category	Requirement
NFR-01: Performance	Sensor-to-cloud latency shall not exceed 5 seconds under normal network conditions.
NFR-02: Reliability	System MTBF shall exceed 720 hours; MQTT delivery rate shall exceed 99% over 7-day periods.
NFR-03: Security	All cloud communications shall use TLS 1.2 or higher encryption; MQTT credentials stored in encrypted NVS partition.
NFR-04: Scalability	Architecture shall support deployment of 1,000+ bins with linear (not exponential) cost scaling.
NFR-05: Maintainability	OTA firmware updates; cloud-based threshold configuration; modular firmware architecture enabling sensor substitution.
NFR-06: Environmental	Hardware shall be rated IP54 or higher for outdoor deployment; operating temperature -10°C to +60°C.
NFR-07: Power	System shall operate on 12V Li-ion battery for minimum 72 hours between charges; average current draw < 200 mA idle.
NFR-08: Data Integrity	JSON payloads shall include checksum validation; duplicate delivery prevention via message ID tracking.
NFR-09: Usability	RGB LED status shall be visible from 10 meters in direct sunlight.
NFR-10: Compliance	Gas sensor thresholds aligned with OSHA / Sri Lanka occupational health guidelines for relevant gases.

TABLE 8 : NONFUNCTIONAL REQUIREMENTS

CHAPTER 6: COMMERCIALIZATION PLAN

6.1 Target Market and Customer Persona

The Environmental Sensing Smart Bin system targets two primary market segments in the immediate term and a broader global market in the medium to long term:

- Primary Segment Municipal Authorities in South and Southeast Asia: Local government bodies in Sri Lanka, India, and Southeast Asian nations facing rapid urbanization and inadequate waste management infrastructure. These organizations are increasingly mandated to implement smart city technologies under national development plans and international sustainability commitments.
- Secondary Segment - Private Waste Management and Recycling Companies: Commercial operators who can monetize operational efficiency gains from dynamic, data-informed collection scheduling and enhanced recycling sorting enabled by composition prediction.
- Tertiary Segment - Industrial and Healthcare Facilities: Facilities with specific hazardous waste monitoring requirements where the gas sensing capability provides direct occupational health value.

The representative customer persona is a mid-sized regional waste management authority managing 200–2,000 public bins across an urban municipality, currently spending 30–50% of operational budget on sub-optimal collection logistics, and facing regulatory pressure to improve environmental compliance metrics.

6.2 Value Proposition

The Smart Environmental Sensing Bin reduces collection operational costs by 25–40% through data-driven dynamic scheduling, prevents hazardous gas incidents through real-time early detection, and generates rich multi-parameter datasets that enable predictive analytics - all at a hardware cost below LKR 15,000 per unit

Quantifiable user benefits include: reduction in unnecessary collection trips (estimated 30 - 40% based on comparable deployments), elimination of bin overflow incidents (estimated 85% reduction), reduction in occupational health incidents related to hazardous gas exposure, and improved recycling segregation efficiency through composition prediction data.

6.3 Revenue Model

Revenue Stream	Description
Hardware Sales	Per-unit smart bin kit sales (ESP32 + sensor suite + enclosure) to municipalities and private operators
Cloud Platform Subscription	Monthly SaaS fee for dashboard access, cloud analytics, and alert management services
System Integration Services	Professional services for deployment, calibration, and system integration with existing fleet management
Data Analytics Reports	Subscription-based operational analytics reports (waste generation patterns, collection optimization insights)
Maintenance and Support Contracts	Annual hardware maintenance, firmware update, and 24/7 technical support services

TABLE 9 : REVENUE MODEL

6.4 Cost Estimation and Pricing Strategy

Cost Component	Estimated Unit Cost (LKR)
ESP32 Development Board	1,200
HC-SR04 Ultrasonic Sensor	350
Load Cell (10 kg) + HX711	1,800

MQ-135 Gas Sensor	600
MQ-4 Gas Sensor	650
DHT22 Temperature/Humidity Sensor	400
RGB LED + Resistors + PCB	250
IP54 Weatherproof Enclosure	1,500
12V Li-ion Battery + Charge Controller	4,500
Wiring, Connectors, Mounting Hardware	800
Assembly and Testing Labor	2,500
TOTAL UNIT COST	14,550
Recommended Retail Price (2x margin)	29,000 – 35,000

TABLE 10 : COST ESTIMATION

Cloud platform subscription pricing is proposed at LKR 500–1,500 per bin per month depending on service tier, providing a recurring revenue stream with high gross margins (estimated 70–85% for SaaS component).

6.5 Competitive Advantage and IP Considerations

The system’s competitive advantages include: the unique multi-parameter sensing integration not offered by any existing commercial competitor, the substantially lower hardware cost compared to international alternatives (Bigbelly retails at approximately USD 3,000-5,000 per unit), the local supply chain and support capability, and the integrated connection to the group’s ML prediction and route optimization platform.

Intellectual property considerations include: the novel firmware architecture for multi-parameter threshold fusion is a candidate for patent protection or trade secret; the calibration methodology and threshold tables represent proprietary operational knowledge. The project team will consult with SLIIT's technology transfer office regarding IP protection and potential commercialization pathway.

CHAPTER 7: BUDGET AND JUSTIFICATION

7.1 Research Budget Breakdown

Category	Item	Estimated Cost (LKR)	Justification
Hardware	ESP32 DevKit V1 x3 (development + testing + prototype)	3,600	Redundancy for firmware development and destructive testing
Hardware	HC-SR04 x4	1,400	Multiple units for comparative calibration testing
Hardware	Load Cell (10 kg) + HX711 x2	3,600	Primary + backup unit
Hardware	MQ-135 x3	1,800	Calibration requires multiple sensors for cross-validation
Hardware	MQ-4 x3	1,950	Same rationale as MQ-135
Hardware	DHT22 x3	1,200	Development + testing + prototype units
Hardware	Breadboard, PCB, components, wires	2,500	Prototyping materials for firmware development phase
Hardware	IP54 Enclosure + mounting materials	2,000	Physical prototype assembly

Hardware	12V Battery + charge controller	4,500	Field deployment power system
Cloud/Software	Firebase Blaze Plan (prototype)	~500/month x4 months	Cloud storage for sensor data during testing phase
Testing	Reference weights set (calibration)	1,500	Required for load cell calibration protocol
Documentation	Fritzing and KiCad licenses (open-source)	0	Free academic licenses
Miscellaneous	Contingency (10%)	2,455	Unforeseen hardware failures or procurement delays
TOTAL		~28,505	

7.2 Budget Justification

The hardware procurement costs will dominate the budget since this is the nature of this embedded systems research component. Several sensors of each type are acquired to allow parallel development and testing processes, destructive/stress testing without stopping the main development and production of a complete calibrated prototype. The cost of cloud services is low because the free tier of Firebase is quite generous and covers the volumes of telemetry corresponding to a prototype.

CHAPTER 8: WORK BREAKDOWN STRUCTURE (WBS)

8.1 WBS Overview

The WBS breaks down the research project into small and manageable tasks that are structured into three project phases and two academic semesters. The period of task execution represents the realistic estimates of the time according to the extent of work development of embedded systems.

8.2 Detailed Task Breakdown

Task ID	Task Description	Timeline	Deliverable
WP1.1	Sensor selection, literature review finalization, procurement	March - April	Component procurement list; updated literature review
WP1.2	Hardware assembly and initial wiring (breadboard prototype) , Individual sensor firmware modules	May - June	Breadboard prototype with all sensors connected , Individual sensor test code for each sensor
WP1.3	Sensor calibration - HC-SR04 and load cell, Sensor calibration - MQ-135, MQ-4, DHT22	June - July	Calibration records and correction constants , Gas sensor calibration curves; DHT22 validation report
WP1.7	Integrated firmware - all sensors reading concurrently , JSON payload serialization module , Wi-Fi connectivity and MQTT/HTTP implementation	July - August	Integrated sensor read firmware; test data logs , JSON output with all fields; validation against schema , Reliable cloud connection tested over 24 hours
WP2.3	Firebase Realtime Database integration and data structure setup , Threshold classification and RGB LED alert system , Local data buffering (SPIFFS) and offline retry logic	August - September	Live telemetry visible in Firebase console , GREEN/YELLOW/RED transitions validated against test cases , Offline operation test: 24h buffer, successful upload on reconnect
WP2.6	OTA firmware update implementation , PCB design and soldered prototype construction , Field deployment testing (outdoor, multiple waste types)	September - October	Successful OTA update demonstrated from cloud , Soldered PCB prototype with wiring diagram , 7-day continuous deployment test data; anomaly analysis
WP3.3	Performance evaluation against defined metrics , Dataset compilation and export for ML components , Technical documentation: wiring diagrams, firmware docs	October - November	Performance evaluation report with metric results , Validated CSV/JSON dataset provided to group members, Complete technical documentation package
WP3.6	Proposal report writing and submission , Final dissertation chapter writing	November - December	Submitted proposal report , Complete dissertation chapters for this component

8.3 GANTT Chart

The table below gives a simplified version of the Gantt chart of the project schedule within a duration of 20 weeks in 2 semesters. Gantt chart will be detailed and kept in Microsoft project and will be attached as Appendix D..

Work Package	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Topic Selection & Initial Research												
Literature Review & Requirement Analysis												
System Design & Methodology Development												
Proposal Preparation and Submission												
<i>Proposal Submission</i>												
Data Collection and Dataset Preparation												
Core System Development (IoT + ML)												
<i>Progress Presentation 1</i>												
System Integration and Optimization												
<i>Progress Presentation 2</i>												
System Testing and Performance Evaluation												
Final Report and Website Preparation												
<i>Final Report Submission</i>												
<i>Website Submission</i>												
Final Presentation and Research Paper Submission												
<i>Final Presentation & Viva</i>												
<i>Research Paper Submission</i>												
<i>Research Publication Evidence</i>												

CHAPTER 9: SELF-EVALUATION PLAN

9.1 Evaluation Framework

The self-evaluation plan offers a systematic framework of the evaluation of the effectiveness of the implementation of the environmental sensing smart bin in relation to the set, measurable standards. There are three dimensions of evaluation, including the technical performance, the quality of research, and the delivery of projects.

9.2 Technical Performance Evaluation

Evaluation Criterion	Success Metric and Test Method
Fill Level Accuracy	Measure 30 independent readings at known distances; compute RMSE; target: $\pm 5\%$
Weight Measurement Accuracy	10-point calibration curve with reference weights; target: $\pm 200\text{g}$ across 0–50kg
Gas Detection Sensitivity	Expose sensor to controlled gas concentrations; verify alert triggering at defined thresholds; target: $>95\%$ true positive rate
Temperature/Humidity Accuracy	Compare 24 paired readings with certified reference; target: $\pm 1^\circ\text{C}$ temperature, $\pm 3\%$ RH
Cloud Delivery Rate	Log 1,008 consecutive transmissions (7 days x 144/day); count successful deliveries; target: $>99\%$
Cloud Latency	Timestamp at ESP32 and at Firebase; compute delta for 100 readings; target: <5 seconds
System Uptime	24/7 operation for 30 days; log restart events; target: < 1 unplanned restart per 720 hours
Alert Accuracy	Inject 50 test scenarios with known expected status; compute precision and recall; target: $> 97\%$

9.3 Research Quality Evaluation

- Literature Review Coverage: Minimum 12 peer-reviewed sources from IEEE, Elsevier, and Springer venues published within the last 7 years, critically analyzed and synthesized.
- Novelty Validation: Self-assessment against comparative analysis table (Section 1.2.6) confirming no existing system provides equivalent multi-parameter integration.
- Reproducibility: Complete wiring diagrams, calibration procedures, and firmware code published on GitHub repository; sufficient for replication by a competent embedded systems engineer.
- Dataset Quality: Minimum 30 days of continuous, validated sensor data with <5% missing values, suitable as ML training data.

9.4 Project Delivery Evaluation

Deliverable	Completion Criterion
Working Smart Bin Prototype	All sensors operational; real-time telemetry confirmed in Firebase console
Complete Wiring/Prototype Diagram	Fritzing and KiCad diagrams covering all connections; peer-reviewed by group member
Well-commented ESP32 Firmware Code	All functions documented; README with setup instructions; published to GitHub
Calibration and Test Results Report	Quantitative results for all metrics; statistical analysis (mean, std dev, RMSE)
Sample Data Charts	Time-series visualizations of all sensor parameters over 7-day test period
Proposal Report	Submitted on time; meets all marking scheme criteria

Dataset Export for Group Members	CSV/JSON format; documented schema; tested import by group ML member
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APPENDICES

Appendix B: Preliminary Risk Analysis

Risk	Likelihood / Impact / Mitigation
MQ sensor calibration drift in outdoor temperatures	Medium / High / Monthly recalibration schedule; temperature compensation in firmware
ESP32 Wi-Fi connectivity instability in outdoor environments	Medium / Medium / SPIFFS local buffering; exponential backoff reconnection algorithm
Load cell mechanical damage from overloading	Low / High / Software upper limit (50 kg) with audible alert; mechanical overload stopper
Firebase free-tier rate limiting during peak test periods	Low / Low / Upgrade to Blaze plan; batch transmission optimization
Component procurement delays in Sri Lanka	Medium / Medium / Early procurement (Week 1); identify backup local suppliers
Firmware stability issues after OTA updates	Low / High / Staged rollout; automatic rollback to previous firmware on failure

Appendix D: Reference to System Architecture Diagram

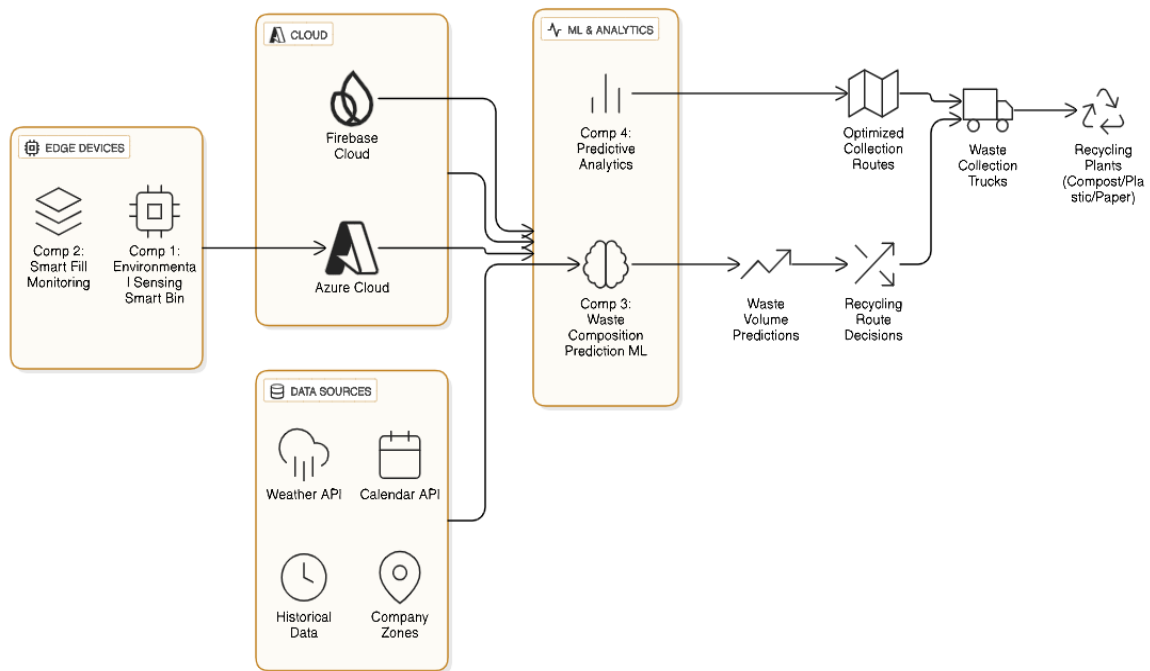


FIGURE 3 SYSTEM ARCHITECTURE DIAGRAM

Appendix E: Preliminary ESP32 Sensor Read Code Snippet

```
#include <DHT.h> #include <HX711.h> #include <NewPing.h> #include <ArduinoJson.h> #define DHTPIN 4 #define DHTTYPE DHT22 #define TRIG_PIN 5 #define ECHO_PIN 18 #define HX711_DT 21 #define HX711_SCK 22 #define MQ135_PIN 34 #define MQ4_PIN 36 DHT dht(DHTPIN, DHTTYPE); HX711 scale; NewPing sonar(TRIG_PIN, ECHO_PIN, 400); void setup() { Serial.begin(115200); dht.begin(); scale.begin(HX711_DT, HX711_SCK); scale.set_scale(CALIBRATION_FACTOR); scale.tare(); } void loop() { float fill_cm = sonar.ping_cm(); float weight_kg = scale.get_units(10) / 1000.0; int mq135_val = analogRead(MQ135_PIN); int mq4_val = analogRead(MQ4_PIN); float temp = dht.readTemperature(); float hum = dht.readHumidity(); // ... threshold evaluation and JSON serialization ... delay(60000); }
```

Appendix F: Work Breakdown Structure

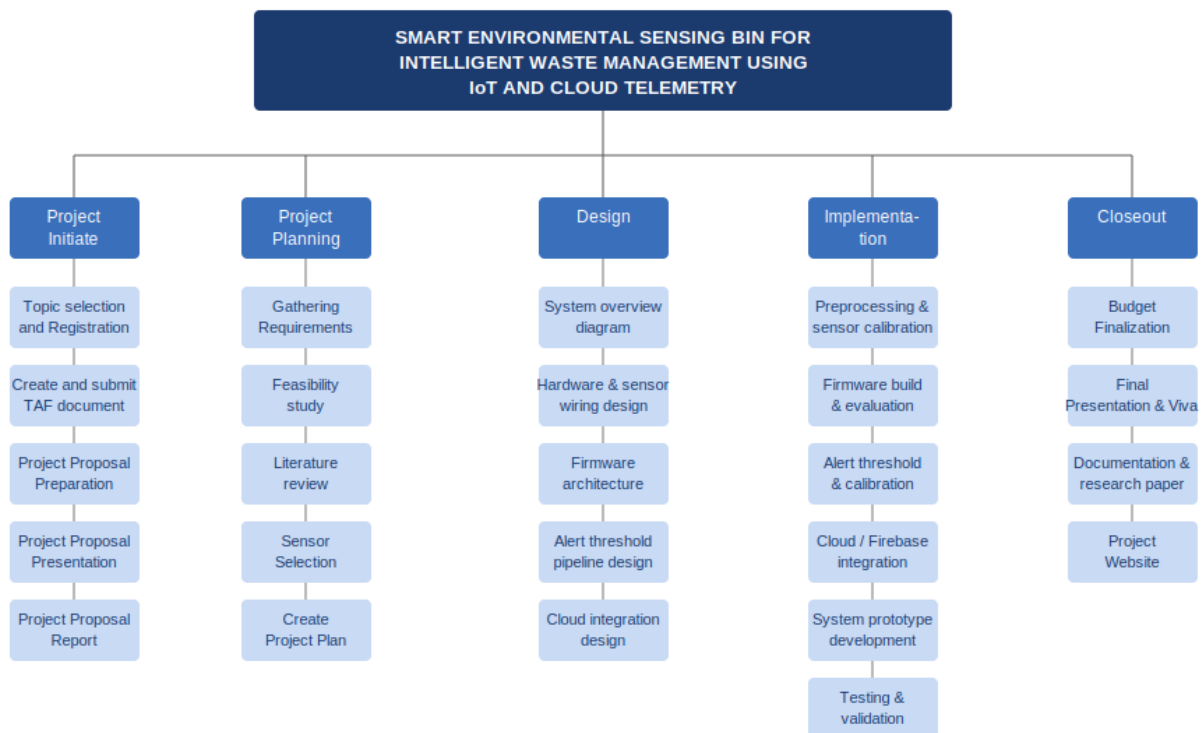


FIGURE 4 : WORK BREACKDOWN STRUCTURE