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ISPO RESEARCH REPORT

BINSAI: Development of a Non-Contact Distance Sensor-Based Waste Bin Monitoring System and Internet of Things (IoT) Node Integrated with the Blynk Mobile Application to Support Smart Waste Management in the City of Yogyakarta

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Abstract

The problem of waste accumulation in urban areas, particularly in the city of Yogyakarta due to the limited capacity of the Piyungan landfill, requires a more intelligent and responsive management approach. This study aims to develop and test BINSAI (Bin Intelligence Sensor and Internet), a prototype of an integrated Internet of Things (IoT)-based waste bin monitoring system. This system is designed to optimize waste transportation operations through real-time monitoring of capacity and indications of organic waste decomposition. The research method uses a Research and Development (R&D) approach utilizing an ESP32 microcontroller integrated with an HC-SR04 ultrasonic sensor for volume measurement and an MQ-135 gas sensor to detect ammonia concentration. The data is processed and transmitted to the Blynk platform for visualization, while the GSM SIM800L and GPS NEO-6M modules provide priority notifications and location tracking via SMS when critical conditions are detected. Test results show that the ultrasonic sensor has an accuracy of 99.46%, the gas detection model has a validity (R^2 = 0.987), and notification transmission has a reliability of 100%. The modular smart bin concept allows for flexible implementation in public areas with high volume fluctuations. This study concludes that BINSAI has the potential to be a transformative solution in supporting smart waste management, improving operational efficiency, and contributing to reducing landfill burden. All technical documentation and source code are published openly on the GitHub repository to ensure transparency and sustainability of development.

Keywords: Smart Waste Management, Internet of Things (IoT), Ultrasonic Sensor, Gas Sensor, Blynk, Modularity, Yogyakarta City.

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

Indonesia, as the largest archipelagic country in the world, faces serious challenges in waste management in line with population growth, economic growth, and community consumption. Waste management is a collective responsibility whose effectiveness is still constrained by many factors, one of which is limited facilities (Arifin, 2024; Vedita, 2022). Based on data from the Ministry of Environment and Forestry (KLHK), national waste generation in 2023 reached 69.7 million tons (Sumbitmele, 2024). The accumulation of unmanaged waste can trigger environmental degradation, flood risks, threats to public health, and damage to the aesthetics of the urban environment.

This problem is even more apparent in big cities, including Yogyakarta, where waste evacuation to the Piyungan landfill has stagnated due to capacity limitations (Pangaribowo & Hartik, 2025). Between 2021 and 2025, there has been an accumulation of waste at the Piyungan landfill, with the highest amount reaching 700 tons of waste per day (Bantul Regency Government, 2025). This crisis is exacerbated by a surge in the number of tourists, estimated to reach 1.1 million people, which is predicted to add around 550 tons of additional waste per day (Suhamdani, 2025). Meanwhile, the city of Yogyakarta currently produces around 300 tons of waste per day, while the quota allowed to enter the landfill is only 600 tons per month (Adminwarta, 2025). “Only cities that evacuate to the Piyungan landfill,” said Aris Prasena, Head of the DLHK Waste Management Office, DIY. In addition, the temporary closure of the Piyungan Final Disposal Site (TPA) began in mid-2024 (Daeng, 2024).

Given the accelerating complexity of urban dynamics, the conventional fixed-schedule waste management approach has reached a point of stagnation and is no longer adequate to mitigate the rate of waste generation. This phenomenon demands a paradigm shift towards evidence-based waste management that integrates the Internet of Things (IoT) ecosystem as its main pillar. The implementation of sensor convergence, which includes ultrasonic sensors for volumetric analysis and ammonia gas sensors to detect the kinetics of organic decomposition, enables real-time telemetry extraction. Through the synchronization of this data, the system is able to reduce information ambivalence in the field, so that the process of mobilizing the transportation fleet can be carried out based on precision prioritization that optimizes resource allocation and increases operational agility in urban waste management.

This research developed BINSAI (Bin Intelligence Sensor and Internet) as a prototype for a smart trash bin monitoring system integrated with the Blynk platform. This research was limited to a prototype monitoring system with two main parameters, namely capacity and dispersion of gases resulting from organic decompositionWaste classification is indicative based on empirical thresholds, not chemical identification. Unlike static systems, BINSAI is designed modularly with a location-based (GPS and GSM) priority notification system to improve the operational agility of officers. To ensure research reproducibility and data transparency, all source code and technical documentation for the BINSAI system are published openly through the GitHub repository under the MIT License.

The implementation of this IoT system is the first step in accelerating the digital transformation of waste management in Yogyakarta. This not only supports the reduction of the burden on the Piyungan landfill, but also strengthens the pillars of a Smart City through the provision of measurable and scientific time-series datasets (Sa'diyah et al., 2020; Lianawati, 2024).

1.2 PROBLEM FORMULATION

The problem formulation related to this research is as follows.

1. How to design an Internet of Things (IoT)-based BINSAI system that integrates height detection, waste decomposition indication of ammonia gas levels, and geolocation into the Blynk dashboard in real-time?
2. How responsive and accurate is the adaptive threshold-based notification prioritization system in optimizing waste transportation management?
3. How to design a modular smart bin concept to accommodate fluctuations in waste volume in public areas with high activity spikes?
4. How to manage BINSAI technical documentation and source code in an open repository to ensure research reproducibility for future Smart City development?

1.3 RESEARCH OBJECTIVES

Based on the problem formulation, the research objectives can be summarized as follows.

1. Designing an ESP32 microcontroller-based BINSAI system capable of accurately extracting telemetry data on capacity and decomposition indicators through remote data acquisition.
2. Analyzing the performance of a prioritized notification system in providing precise information on the urgency of handling critical waste points.
3. Design and test the operational agility of the modular smart bin concept in an effective BINSAI platform to support waste management in public areas and areas with high activity.
4. Accelerate research transparency and reproducibility through comprehensive publication of all source code and technical documentation of hardware on the GitHub repository under an open license.

1.4 RESEARCH BENEFITS

Based on the research questions and objectives, the benefits of this research are as follows.

1.4.1 Theoretical Benefits

This research contributes to the enrichment of the Internet of Things (IoT) literature through the development of BINSAI, which integrates convergent multi-sensors (distance and gas) in real-time. This innovation enables preventive operational mitigation, such as the preparation of special materials before evacuation, reinforces the concept of open science in technology development, and strengthens the concept of modular smart bins as a pillar of environmentally friendly technology in supporting the Smart City ecosystem.

1.4.2 Practical Benefits

1. Optimization of Landfill Quota Allocation: Transformation of waste management through location-based precision prioritization and real-time data. With adaptive thresholds, the system ensures that the limited quota of the Piyungan landfill is selectively allocated at critical points (>90% + organic), in order to significantly reduce the environmental burden compared to conventional distribution.
2. Although data transmission in this proof of concept phase is still locality-dependent, the BINSAI architecture is designed with high interoperability to integrate public infrastructure and private sector CSR synergies.
3. Modular Operational Agility: Implementation of a flexible, plug-and-play modular smart bin concept enables dynamic mobilization of devices to anticipate spikes in waste volume in strategic areas and public activity centers.

CHAPTER 2. LITERATURE REVIEW

2.1 Theoretical Study

The BINSAI research is based on the integration of embedded systems, smart sensors, and wireless communication to realize responsive waste management.

2.1.1 Hardware Architecture: ESP32 and Sensors

The main control unit uses an ESP32 microcontroller, a dual-core System on a Chip (SoC) that integrates Wi-Fi and Bluetooth connectivity for efficient IoT data transmission (Nizam et al., 2022). Waste volume data acquisition is performed by an HC-SR04 Ultrasonic Sensor that utilizes the principle of wave reflection with a precision of up to 3 mm (Prastyo, 2022). Meanwhile, air quality is monitored through an MQ-135 Gas Sensor that can detect increases in the concentration of various volatile gases, one of which is ammonia as an indicative proxy for organic decomposition (Swagatam, 2019). The synergy between these components enables simultaneous monitoring of the physical and chemical conditions of the trash bin.

2.1.2 Smart Waste Management and Modularity Concept

Smart waste management is defined as the optimization of waste logistics through real-time data to reduce operational costs and improve resource efficiency (Longhi et al., 2012). BINSAI adopts the Modular Smart Bin concept, which is an adaptive smart sensor unit that can be mobilized to high-density areas according to operational needs (Zhao et al., 2022). This implementation supports the principle of sustainable development through proactive waste management.

2.1.3 Early Warning System and Geolocation

The integration of GPS NEO-6M and the SIM800L module acts as an Early Warning System (EWS) mechanism. GPS NEO-6M provides precise spatial data (latitude and longitude) through satellite signal extraction (Prastyo, 2024). The data is sent via SIM800L as a redundant SMS-based communication channel, ensuring information connectivity even in the event of internet network disruptions (Bitfoic, 2023). This is crucial for more measurable waste transportation logistics management (Ghiani et al., 2014).

2.1.4 IoT Ecosystem: Blynk and BINSAI Products Blynk

The Blynk platform acts as a cloud platform for real-time visualization and remote control of devices (Hakim, 2023). Through this platform, BINSAI (Bin Intelligence Sensor and Internet) integrates threshold-based algorithms to classify waste conditions deterministically. BINSAI transforms conventional waste bins into smart sensor nodes capable of providing location-based priority notifications, improving response efficiency without high algorithm complexity. The graphical interface on the Blynk mobile application is as follows.

Figure 1: Blynk Mobile Application Interface
(Source: https://shorturl.at/8G8QK)

2.2 Relevant Research

A number of previous studies have validated the effectiveness of IoT in waste management. Qur'ainny et al. (2024) stated that the use of IoT and digital applications can improve the effectiveness of waste management, particularly in terms of waste transportation and monitoring. In addition, the application of this technology has also been proven to increase public awareness in sorting and managing waste independently.

Another study by Gusdevi et al. (2023) shows that the application of IoT can be an effective and efficient solution in waste management systems. This technology enables real-time monitoring of waste bin conditions and supports faster and more accurate decision-making by sanitation workers. Furthermore, Prabowo et al. (2025) developed a system based on the Arduino Uno microcontroller equipped with ultrasonic sensors to detect the presence of users. This system allows the trash bin door to open and close automatically, thereby increasing user convenience and waste management efficiency.

Unlike the research by Prabowo et al. (2025), which focuses on physical automation, or the research by Qur'ainny et al. (2024), which is general in nature, focusing on the integration of bimodal sensors (volume and gas) with prioritization mechanisms and redundant communication, BINSAI presents itself as a fundamental solution in realizing precise and sustainable waste management, especially in addressing urban challenges in the city of Yogyakarta.

CHAPTER 3. RESEARCH MATERIALS AND METHODS

3.1 Research Time and Location

This research was conducted over a total period of five months, from the preparation stage to the reporting of the final results. The research was centered at the MAS Assalafiyyah Mlangi Laboratory, Sleman, Sleman Regency, Special Region of Yogyakarta.

3.2 Tools and Materials

The technical components used included: HC-SR04 ultrasonic sensor, ESP32 microcontroller, SIM800L GSM module with board, SIM card (active with credit), NEO-6M GPS module, MQ-135 gas sensor, 10,000mAh power bank with 5V 3A output, waterproof casing, Blynk cloud server, breadboard, jumper cables (used during the experimental phase; after final design, connections are made via soldering on a universal PCB), side clamps, I2C LCD, laptop for programming and monitoring, Arduino IDE and VS Code software, soldering tools and assembly equipment, and finally a 50 L capacity trash bin.

3.3 Research Design and Procedures

The research design and procedures are as follows.

3.3.1 Research Design

This study applied an experimental method with a Research and Development (R&D) approach. The BINSAI prototype was designed as an intelligent monitoring system capable of automatically identifying the physical (volume) and chemical (decomposition gas) parameters of waste. The design concept is outlined as follows..

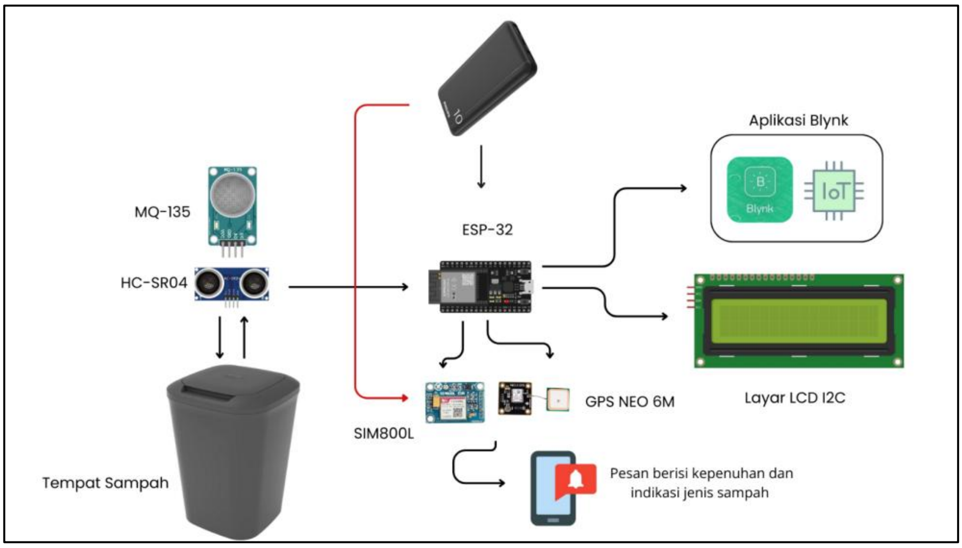

Figure 2: BINSAI Device Design

(Source: Researcher's personal documentation)

3.3.2 Research Procedures

The fabrication stage begins with the preparation of components according to the table in Appendix 1. Technically, the assembly procedure includes:.

1. Sensory Integration: Connecting the HC-SR04 and MQ-135 sensors to the ESP32. Specifically for the MQ-135 sensor, a pre-heat procedure lasting 120 seconds is applied before data reading is performed in order to stabilize the sensor's heating element. RZero Calibration is also performed in a clean air environment (baseline) with MQ-135 sensor calibration to obtain a meaningful relationship between the ADC (Analog-to-Digital Converter) value and ppm (parts per million) of a specific gas (such as ammonia) to determine the reference resistance (Ro) value.
2. Firmware Programming: Uploading program code that includes distance-to-percentage conversion algorithms, waste status classification, and data transmission intervals every 2 seconds to Blynk and research logs every 60 seconds.
3. Procedural Power Management: Implementing delay optimization in the program code to ensure power consumption remains efficient when the system is in standby mode.
4. Finalization: Assembling all components into a waterproof casing and testing functionality in the laboratory before deployment. Once the device is connected according to the techniques mentioned above, it will produce a design as shown in Figure 3 below.

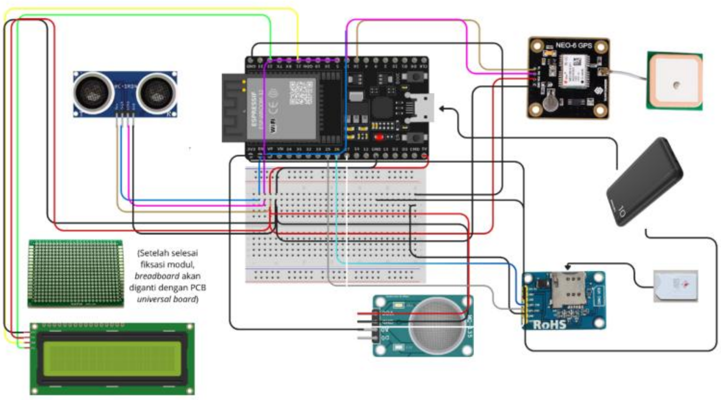

Figure 3: Design of the BINSAI Monitoring Device based on the Internet of Things
(Source: Researcher's Personal Documentation)

3.3.3 Integration of the Blynk Mobile Interface and Spatial Notification Protocol

The Blynk dashboard configuration utilizes Virtual Pin (V-Pin) addressing for real-time data synchronization. The Early Warning System (EWS) protocol is activated via

SIM800L to send geolocation coordinates (latitude and longitude) from GPS NEO-6M via automatic SMS when the bin capacity reaches the threshold (≥90%).

3.3.4 Construction of a High Mobility-Based Smart Bin Modular Unit

The concept of modularity is realized through a compact and self-contained device design. This allows the BINSAI unit to be flexibly moved (plug-and-play) to high-density points. This system ensures that each node remains identified in the central database through synchronization of a unique device ID.

3.3.5 Code and Documentation Repository

To ensure transparency, reproducibility, and contribution to the open-source community, all source code and research datasets have been published on the GitHub repository, as attached in Figure 7 in Appendix 4. This repository adopts version control practices with Git, enabling change tracking and continuous collaboration. The MIT license is applied to support adoption and further development by other researchers.

3.4 Data Processing and Analysis

The processing and analysis of data for this study are as follows.

3.4.1 Data Processing

Data obtained through sensors is transmitted continuously every 2 seconds to the IoT server via Wi-Fi communication protocol for visualization on the Blynk mobile interface. In parallel, the system logs research data to the cloud every 60 seconds for statistical analysis purposes. The data parameters managed include: (a) garbage pile elevation (cm), (b) gas concentration (ppm), (c) transportation priority level, (d) geospatial coordinates, and (e) measurement timestamp.

Raw data from ultrasonic sensors is processed into a percentage of fullness to provide a more intuitive interpretation of volume. This conversion is performed using the following mathematical formula:

$$\text{Percentage of Fullness} = \left(1 - \frac{\text{Measured Distance}}{\text{Maximum Tank Height}}\right) \times 100\%$$

The results of these calculations are then automatically classified by the microcontroller into four operational status categories based on the following predetermined thresholds.

1. 0–35%: “Empty”
2. 36–50%: “Half”
3. 51–90%: “Almost Half”
4. 91–100% : “Full”

3.4.2 Data Analysis

The analysis stage was conducted critically to validate BINSAI's performance through two main approaches. First, sensory accuracy tests were carried out by comparing digital data from sensors with manual measurements using a ruler to calculate the error rate. Second, transmission reliability tests were conducted to calculate the percentage of successful SMS transmission of location coordinates when critical conditions were met.

A special evaluation was conducted on the modularity aspect of BINSAI by reviewing the mobility of the unit and the agility of device activation at high-density points. Modularity performance was measured based on the effectiveness of the unit in anticipating temporary spikes in waste volume.

Table 1: BINSAI Performance Evaluation Parameter Matrix

No	Effectiveness Indicator	Measurement Parameter	Success Target (Threshold)
1	Sensory Accuracy	Deviation between sensor values and manual measurements	Error <3 cm
2	I oT Responsiveness	Data transmission latency from ESP32 to Blynk Cloud	Response time <2 seconds
3	SMS Reliability	atio of location notifications received on time	Success rate >90%
4	Modular Mobility	ime from deployment to system online	Active time <10 minutes
5	Waste Type Indication	Accuracy of organic/inorganic classification via MQ-135	Indication accuracy >98%

The above matrix serves as a comprehensive system validation instrument to ensure the objectivity and functionality of BINSAI in real conditions. The establishment of these quantitative indicators is not merely a formal procedure, but a critical effort to transform this research from the proof of concept stage into a technological solution with scientifically tested system robustness.

CHAPTER IV. RESULTS AND DISCUSSION

4.1 Results of the BINSAI System Plan

The development of BINSAI (Bin Intelligence Sensor and Internet) realizes a Cyber-Physical System (CPS) architecture that integrates sensory instrumentation with cloud connectivity. The system is designed in four strategic modules to address waste management challenges in a measurable manner.

4.1.1 Smart Monitoring Module: Synergy of Volumetric Analysis and Gas Kinetics

The module converges the physical and chemical parameters based on the ESP32 microcontroller, which coordinates the simultaneous data acquisition of two core sensors:

1. HC-SR04 Ultrasonic Sensor: Performs volumetric analysis based on the principle of Time-of-Flight (ToF) to measure the elevation of the garbage pile.
2. MQ-135 Gas Sensor: Serves as a qualitative indicator to detect the presence of ammonia gas (NH_3) as a proxy for the organic decomposition process. The stability of the readings is maintained with the moving average algorithm.

The synergy of data allows for a tiered response mechanism. In contrast to conventional systems that are only reactive to physical capacity, BINSAI can be proactive by setting priorities based on potential environmental risks (such as odor emissions and disease vector attraction) before the tub reaches full capacity. The data processing results are displayed in real-time on the I2C LCD's local interface for field workers and transmitted to Blynk's IoT platform via Wi-Fi for remote monitoring, ensuring transparency and continuity of monitoring with the entire system procedural logic systematically set as illustrated in the flowchart in Figure 4 below.

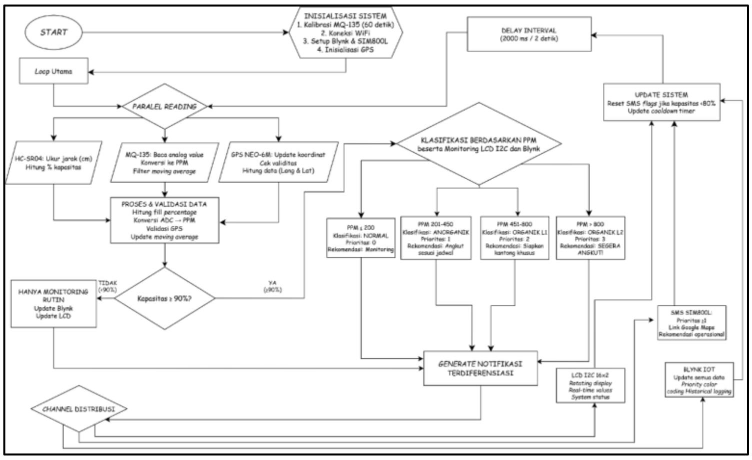

Figure 4: Flowchart of the Development of the BINSAI Monitoring System with Detection Feature of Height and Type of Waste to Differentiated Response (Source: Researcher's Personal Documentation)

The logic architecture of the BINSAI system is optimized by integrating the MQ-135 sensor as an instrument for early detection of organic material decomposition. Its mechanism of action is deterministic, resting on the simultaneous correlation between physical parameters (capacity >90%) and chemical parameters (gas concentration ≥ threshold), which are processed by the ESP32 microcontroller. The stability of the gas sensor readings was improved by the moving average algorithm, resulting in consistent PPM values to distinguish the waste degradation phases from normal, initial indication, to critical levels (Figure 4).

When both critical thresholds are met, the system activates the emergency notification protocol. The protocol includes specific operational recommendations: (1) the use of layered garbage bags for odor retention, (2) the allocation of special compartments on transport trucks, and (3) the designation of high priority status in the schedule. Precise location data transmission via NEO-6M and GSM GPS modules SIM800L enables BINSAI to perform dynamic mapping based on material urgency. Priority categorization is designed based on real-time acquired gas concentration gradients. The PPM threshold is set through empirical calibration that refers to the sensitivity characteristics of the MQ-135 sensor to ammonia and sulfide gases (Hanwei Electronics, 2010). The categories are differentiated into the initiation phase of organic degradation ('Organic Level 1') and the accelerated decomposition phase with high microbial activity ('Organic Level 2') that have potential health risks (Karthi & Sangeetha, 2020). The full categorization is detailed in Table 4 (Appendix 11).

The implication of this tiered response mechanism is the optimization of operational resource allocation. The system allows for a telemetry evidence-based critical distinction between the 'Standard Full Capacity' and 'Critical-Urgent Condition' status (Srivastava et al., 2017). Thus, through an evidence-based approach, BINSAI evolved from a volume monitoring tool to a precise environmental risk management instrument.

The software system is implemented in a modular code architecture that is functional and responsive. In the monitoring module, two main algorithmic routines—defined as a set of deterministic programmatic instructions in the context of IoT—are executed in parallel by ESP32. It operates on the basis of procedural programming principles and structured protocols, which guarantee synchronization between the acquisition of sensory data in the field and the transmission to the cloud server. The operational mechanism of each routine is described in the following section.

4.1.1.1 Routine Garbage Height Measurement and I2C LCD Display

The first routine is focused on processing physical data through the HC-SR04 ultrasonic sensor to determine the elevation of the garbage pile. The measured distance (d) is calculated based on the wave bounce time (t) through the LaTeX equation as follows:

$$\text{Distance (cm)} = \frac{\text{t} \times 0.0343}{2}$$

The distance data is then transformed into a value of the percentage of fullness (K) to the maximum height of the tub (h) with the formulation:

$$\text{K} = \left(1 - \frac{\text{d}}{\text{Maximum Height of The Tub}}\right) \times 100\%$$

The system automatically classifies into four operational states: Empty (0–35%), Half (36–50%), Almost Full (51–90%), and Full (>90%). This information is visualized in real-time via a 16x2 I2C LCD, where the display displays numerical capacity and condition status as well as indications of the type of waste obtained from the MQ-135 sensor alternately. This process runs continuously inside the main loop, so the data on the LCD will always be updated every time the sensor performs a new reading. The source code for routine garbage height measurements and the I2C LCD interface are presented in the complete code in Appendix 3.

4.1.1.2 Routine in the Internet of Things (IoT) through the Blynk Platform

The second routine manages the remote data communication aspect using Blynk.io platform. After the WiFi network initialization and token authentication phase, ESP32 transmits the capacity data to the Virtual Pin V0 to be displayed on the Gauge widget. Simultaneously, the system controls four virtual LED widgets (V1-V4) as quick visual indicators for officers in the control center. This transmission process utilizes the internal MQTT protocol with a frequency of data updates every 1 second to ensure the actuality of the information. Other virtual pin numbering is available in Appendix 2. Meanwhile, algorithmic specifications and the implementation of routine programming code in the Internet of Things (IoT) through the Blynk platform are presented in full in Appendix 3. Thus, this routine functions as a visual interface that supports the concept of smart monitoring in the smart bin system.

Before deployment in the field, a series of functional tests were carried out to ensure the reliability of each technical module. The initial testing stages are documented and fully described in Figure 8 in Appendix 4.

4.1.2 Priority Notification Module and Early Warning System (EWS) through GSM and GPS Component Integration

This module is a redundant mitigation mechanism that integrates the GSM SIM800L and GPS units of the NEO-6M to ensure information continuity in the midst of Wi-Fi network instability. Through the adaptive threshold algorithm, the Early Warning System (EWS) transforms geospatial coordinates into precise logistics instructions in SMS format when the capacity and kinetics parameters of decomposition reach a critical threshold (≥90%). The strategic advantage of mobile network utilization lies in its reliability and inclusivity; Notifications are still distributed to all types of officers' handheld devices without dependency on data packages or third-party applications. This third routine implementation of hybrid communication facilitates the selective and efficient mobilization of fleets, while ensuring transparency of the location of critical points in large public areas. The explanation is as follows.

4.1.2.1 Hybrid Communication Routine: Spatial Geopolitics and SMS Notifications

The third routine in the BINSAI system is a hybrid communication subsystem that integrates the NEO-6M GPS and GSM SIM800L modules to ensure the availability of data in the blank-spot internet conditions. Regarding the connection route of communication pins, including UART Serial pins, has been listed in Appendix 1. The logic of this routine which operates through two deterministic stages is as follows.

1. Geospatial Data Extraction: The microcontroller parses NMEA-formatted raw data from the GPS module using the TinyGPS++ library. This process aims to obtain continuously valid latitude and longitude coordinates.
2. Transmission of Priority Notifications: When the capacity variable reaches a critical threshold (>90%), the system activates the AT Command instruction to send an SMS containing a link to Google Maps the location of the bin. In order to maintain operational cost efficiency and prevent data redundancy, the smsSent logic variable is implemented. This mechanism ensures that notifications are only sent once per charge cycle, and will only be reset once the sensor detects physical body emptying. Appendix 3 contains the implementation of the early warning system algorithm and complete geolocation-based real-time location tracking . An example of the format of a sent message is available in Figure 9 in Appendix 4

4.1.3 Smart Bin Modular Architecture for High Mobility

Global awareness, particularly in the Southeast Asian region, has reached a crucial point where conventional waste management methods are no longer considered relevant due to cost and time inefficiencies. The development of modular smart bin on the BINSAI platform is present as a technological response to the escalation of the urban population (Mark, 2025). This system prioritizes the principle of high portability, where self-contained units can be functionally integrated into the trash can in less than 10 minutes. Economically, this operational agility is supported by a study by Kermanshachi & Rouhanizadeh (2020) on the potential for Return on Investment (ROI) which is 40% faster than static systems, in line with the principle of Time Value of Money. In Yogyakarta, BINSAI's flexibility enables dynamic deployment based on time-series datasets, transforming waste management from a mere public service to a smart investment instrument for local governments, as envisaged by Figure 10 in Appendix 7.

4.1.4 Open Repository and Documentation Module Open Science

As a contribution to a transparent Smart City ecosystem , all of the research's intellectual assets—including ESP32 firmware, hardware schematics, and libraries—are published through a GitHub repository under the MIT license. This step ensures research reproducibility and opens up opportunities for further feature development collaboration by the global community with procedural ease by the README.md already included, as contained in Figure 7 in Appendix 4.

4.2 System Implementation and Integration

The implementation stage translates architectural design into functional physical artifacts. Hardware integration is carried out by connecting HC-SR04, MQ-135, GPS, and GSM sensors on the ESP32 microcontroller via a custom circuit board (custom PCB/Universal Board) to minimize signal noise.

Interface Interconnection: The ESP32 backend system is connected to the Blynk application frontend via the Virtual Pin protocol.

1. Data Visualization: Gas capacity and concentration data are displayed via Gauge Widgets (V0 and V10) for real-time monitoring.
2. Status Indicator: Operational status is converted to a spectral color indicator on the Widget LED (Green: Safe to Red: Critical). Documentation of the physical implementation and digital interface is shown in Figure 11 Appendix 4.

4.3 Test and Analysis Results

System performance validation is carried out through a quantitative empirical approach to measure the accuracy, linearity, and reliability of data transmission.

4.3.1 Multi-Sensor Testing (HC-SR04 dan MQ-135)

The testbegan by analyzing the linearity of the HC-SR04 ultrasonic sensor by comparing the sensor readings to manual measurements at the 40 cm tub height variation as follows.

1. Experimental Accuracy: The test results showed an average accuracy rate of 99.46% with a relative error of 0.54%. The maximum absolute deviation was recorded at only 0.2 cm at full capacity (37.1 cm).
2. Blind Zone Analysis: A blind zone was identified at a distance of < 3 cm from the transducer. The system has been calibrated to handle this anomaly by setting a safe default state to prevent aliasing errors.
3. Conclusion: The linearity characteristics of the sensor attest to the high reliability in the conversion of analog data to a percentage of digital capacity, as represented by Figure 5 as follows.

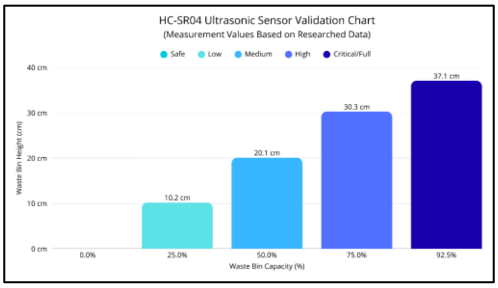

Figure 5: HC-SR04 Sensor Validation Graph

(Source: Researcher's Personal Documentation)

After the data were obtained from the HC-SR04 test, the study continued by analyzing the selectivity of the MQ-135 gas sensor by transforming the raw ADC data into PPM (Parts Per Million) units using the Power-Law Regression approach as shown in Figure 6 as follows.

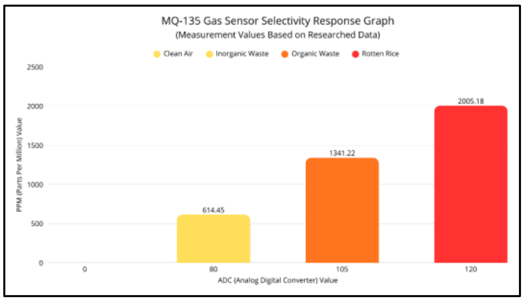

Figure 6: Bar Diagram of MQ-135 Sensor Response

(Source: Researcher's Personal Documentation)

The resulting empirical equations are:

$$PPM = 0.002348 \text{ x } ADC2.856$$

This model has very strong statistical validity with a coefficient of determination (R2) of 0.987 or 98.7%. The measurement was carried out by differentiating the following two phases, namely the clean air phase and the critical decomposition phase using rotten rice as shown in Figure 12 in Appendix 4 accompanied by an explanation.

Critically, the use of this non-linear model is particularly relevant to the physical characteristics of chemical sensors that have an exponential sensitivity curve to organic gas pollutants. Test results show sharp functional contrast; where clean air conditions produced an average of < 60 ADC (PPM < 200), while exposure to rotten rice triggered a spike in ADC > 120 correlated with a gas concentration of > 800 PPM. This validation proves that BINSAI is effectively able to deterministically classify materials through chemical gradient analysis, distinguishing between stable inorganic waste and organic waste that has reached the critical phase of decomposition.

4.3.2 Telemetry and Geolocation Evaluation (GPS & GSM)

The measurement of the level of spatial data accuracy of the NEO-6M GPS module is carried out by validating the coordinates by comparing the GPS module's telemetry data against high-precision geospatial reference points (Google Maps). The documentation that indicates the coordinate value is in Figure 13 in Appendix 4 then continued with the following error calculation.

$$\text{Error} = -7.764200 - (-7.764205)| = 0.000005^{\circ}$$

Accuracy Rate: Analysis shows spatial accuracy to reach 99.99%. The microscopic deviation in the fifth decimal was identified as the truncation effect of the float variable on IoT transmission, which technically did not affect the navigation precision of the logistics fleet (radius tolerance < 1 meter).

Based on the comparison between the readings of the BINSAI device contained in Figure 13 in Appendix 4, the following explanation is obtained.

Percentage Accuracy Formula:

$$\text{Accuracy (\%)} = \left(1 - \frac{|\text{Reference Value} - \text{Measured Value}|}{|\text{Reference Value}|}\right) \times 100\backslash\%$$

Case Calculation (Lat):

1. Reference (Laptop): -7.764200 (6 decimal assumptions)

2. Measurable (Blynk): -7.764205 (5th decimal deviation is available)
3. Error: 0.000005◦
4. Result: Spatial Accuracy ≈ 99.99%

The difference in numbers after the comma is not due to sensor failure, but to the precision of the transmission of float variables in the IoT protocol. ESP32 sends coordinate data as a float variable that is often rounded or truncated when processed by the Blynk server. A deviation of 0.000005 degrees is equivalent to a precision ≈ 0.5 meters, which is technically very acceptable for trash fleet navigation.

Meanwhile, regarding the GSM module, based on mathematical calculations regarding accuracy and efficiency, measurements are obtained through the parameters of accuracy and system redundancy. Based on the trial of 10 message entities, the following indicators were obtained.

1. Transmission Accuracy (Success Rate):

$$\mathrm{SR} = \left(\frac{\sum \mathrm{P}_{\mathrm{success}}}{\sum \mathrm{P}_{\mathrm{total}}}\right) \times 100\% = 100\%$$

These results demonstrate absolute reliability in the transmission of information from nodes to users.

2. Laju redundancy (redundancy rate):

A transmission deviation in the form of one duplicate message (10%) was identified calculated through the redundancy ratio:

$$\%\mathrm{Error} = \left(\frac{\mathrm{P}_{\mathrm{duplicate}}}{\mathrm{P}_{\mathrm{total}}}\right) \times 100\% = 10\%$$

The relationship between the experimental variable (x) and the received data (y) was mapped through a simple linear regression model $y = 1.1x$. A deterministic coefficient that exceeds the ideal value (1.0) indicates a data over-provisioning scheme of 10%.

Critically, this phenomenon is a manifestation of the guaranteed delivery mechanism in response to handshake latency on the cellular network. The BINSAI device initiates retransmission automatically to mitigate the risk of packet loss due to signal fluctuations. This confirms the advantages of a system that prioritizes data integrity over bandwidth efficiency, a crucial parameter for the functionality of the Early Warning System (EWS) in responsive and deterministic urban waste management.

4.3.3 Integrated System Integration

Holistically, the test results in sub-chapters 4.3.1 and 4.3.2 prove that the integration of BINSAI modular components has met the operational standards of Smart City. The convergence between sensory accuracy (98-99%) and telemetry reliability (100% success rate) confirms the feasibility of this system to be implemented as an evidence-based waste crisis mitigation solution.

4.4 Results Discussion

The synthesis of experimental findings confirms the effectiveness of BINSAI as a data-driven mitigation instrument, with the following critical achievements and limitations.

4.4.1 Multidimensional Data Synergy and Proactive Paradigm Shift

The main value of BINSAI lies in the Tiered Response mechanism resulting from sensory data convergence. The high accuracy of the ultrasonic sensor (99.46%) validates the volumetric occupancy, while the integration of the MQ-135 sensor (R^2=0.987) adds a qualitative dimension. This synergy transforms the system from a reactive (full capacity-based) approach to proactive. Early detection of increased ammonia gas allows prioritization of transportation based on the level of environmental hazard (odor, potential pathogen), rather than just physical occupancy, thereby significantly reducing public health risks in congested areas.

4.4.2 Telemetry Architecture Resiliency under Realistic Conditions

The evaluation of the communication module proves its reliability for an urban scale. The phenomenon of data over-provisioning of 10% (modeled with regression y=1.1x) is a manifestation of a deliberate guaranteed delivery mechanism , ensuring that notification integrity is maintained even in conditions of high mobile network latency. 99.99% GPS spatial accuracy provides absolute location precision. This combination of location precision and transmission certainty creates a fleet dispatch system that is much more efficient than conventional static routes, potentially reducing logistics operational costs substantially.

4.4.3 Evaluation of Physical Limitations and Systemic Compensation

The research critically identified technical limitations, such as **blind zones** at a distance of <3 cm from ultrasonic sensors. However, this limitation is successfully compensated by firmware logic that deterministically assigns a "Critical" state when an object enters the zone, thus not detracting from functional utility because that condition already represents excess capacity.

4.4.4 Strategic Relevance to Smart City Implementation

The implementation of BINSAI has direct relevance to the context of the landfill crisis in Yogyakarta. The open-source and modular architecture offers a solution with a low entry barrier but high impact. Blynk's cloud dashboard facilitates real-time data transparency for policymakers. Theoretically, massive implementation could shift the paradigm from Routine Collection to Demand-Driven Collection, which not only solves aesthetic and health issues, but also supports the achievement of the Sustainable Development Goals (SDGs) through the digitalization of inclusive public infrastructure.

4.5 Obstacles and Solutions

The development of BINSAI is faced with technical obstacles that require strategic solutions to ensure functional sustainability.

4.5.1 Technical Constraints

The main obstacle was identified in the failure of the NEO-6M GPS module due to **power instability**. Analysis showed the failure was caused by the use of a 3.3V shared pinout of the ESP32 which was unable to supply a constant current at peak load, causing component degradation. The corrective solution is implemented through power supply isolation by integrating a Dedicated Low-Dropout Regulator (LDO). This self-regulating regulator is proven to stabilize voltage fluctuations and provide protection against current surges, thus guaranteeing the long-term integrity of the GPS module.

4.5.2 Computational Limitations and Technology Inclusivity Strategies

The second technical constraint arose from the ESP32's limited computing capacity which was insufficient to run complex dynamic route optimization algorithms (multi-point routing). Reliance on external servers risks hindering scalability. As a pragmatic solution, the system was reconfigured to focus on an SMS notification mechanism that included Google Maps geospatial links. This strategy not only reduces the burden of on-board computing, but also creates an inclusive ecosystem. The SMS format ensures information accessibility for field officers without reliance on stable internet connections or advanced devices, thus maintaining system functionality in real operational conditions.

CHAPTER V. CONCLUSIONS AND SUGGESTIONS

5.1 Conclusion

This research successfully validated the BINSAI (Bin Intelligence Sensor and Internet) system as a strategic instrument for the digital transformation of urban waste management. Based on empirical evaluation, the following conclusions were drawn.

1. Volumetric Precision & Telemetry: The implementation of Time-of-Flight-based ultrasonic sensors achieves an average accuracy of 99.46%. The transformation of physical data to digital has proven to be reliable with 100% notification transmission reliability through dual channels (Blynk dashboard & SMS Gateway).
2. Deterministic Classification: The integration of the MQ-135 sensor using the Power-Law regression model resulted in high validity (R2 = 0.987). This gives a new dimension of intelligence to the system to precisely differentiate stable inorganic waste and active organic decomposition.
3. Elimination of Operational Blind Spots: BINSAI's modular design effectively negates the inefficiencies of conventional monitoring. This system offers a scalable and proactive solution, making it a feasible model for accelerating Smart City infrastructure in Yogyakarta.

5.2 Suggestions

To elevate BINSAI into a predictive and sustainable waste management ecosystem, the following developments are recommended:

1. Elevation of Artificial Intelligence: Integration of Edge Computing and Machine Vision on firmware to enable automated, real-time sorting at source.
2. Infrastructure Resiliency: Adoption of hybrid communication networks (LoRaWAN) and solar panel-based power management to ensure self-sustaining operations in areas with signal or electricity constraints (off-grid).
3. Data-Based Policy: Development of a dashboard with predictive analytics features to support strategic decision-making (evidence-based policy) by environmental authorities.
4. Triple Helix Synergy: Strengthening Government-Academic-Community collaboration through participatory incentive schemes to encourage collective behavior change in waste management.

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APPENDIX

Appendix 1: Table of Connecting Routes Between Components

Components	Pin ESP32	Component Pins	Main Functions
Power Management			
Power Bank 10.000mAh	VIN/5VIN (SIM800L)	OUT (+)	Power distribution
Power Bank 10.000mAh	GND	OUT (-)	Common Grounding System
Sensor Ultrasonik HC-SR04			
	GPIO 5	TRIG	Trigger Pulse
	GPIO 18	ECHO	Echo Signal
	5V	VCC	Sensor power source
	GND	GND	Negative path
Sensor Gas MQ-135			
	GPIO 34	AUGUST	Gas concentration analog data (PPM) transmission
	3.3V	VCC	Sensor power source (Logic 3.3V)
	GND	GND	Negative path
LCD I2C (16x2)			
	GPIO 21	SDA	Serial Data Line (I2C protocol)
	GPIO 22	SCL	Serial Clock Line (I2C protocol)
	5V	VCC	Backlight and LCD logic power source
	GND	GND	Negative path
GPS NEO-6M			
	GPIO 13	TX	Data Transmission coordinates to ESP32 (RX1)

	GPIO 15	RX	Data Reception command from ESP32 (TX1)
	3.3V	VCC	GPS module resources
	GND	GND	Negative path
Module GSM SIM800L			
	GPIO 16	TX	SMS/GPRS serial data transmission (RX2)
	GPIO 17	RX	SMS/GPRS serial data reception (TX2)
	GPIO 27	PWRKEY	Programmatically Power-on/Reset control of the module
	Out Step-down	5VIN	Dedicated power supply
	GND	GND	Negative Path (Shared Ground)

Appendix 2: Blynk Cloud Datastream and Dashboard Configuration Table

No	Nama Datastream	Virtual Pin	Data Type	Value Range	Units	Widget & Function Description
1	Fill Percentage	V0	Integer	0 – 100	%	Gauge & SuperChart: Continuous monitoring of the volume of waste.
2	LED Red	V1	Integer	0 / 255	-	Widget LED: "FULL" status indicator (>90%).
3	LED Orange	V2	Integer	0 / 255	-	Widget LED: "ALMOST FULL" status indicator (51-90%).
4	LED Yellow	V3	Integer	0 / 255	-	LED Widget: Status indicator "HALF" (36-50%).
5	LED Green	V4	Integer	0 / 255	-	LED Widget: Status indicator "EMPTY" (0-35%).
6	Distance	V5	Double	0 – 400	cm	Labeled Value: Raw data of ultrasonic sensor readings.
7	Capacity Status	V6	String	-	-	Labeled Value: A textual interpretation of the condition of the garbage can.
8	PPM Value	V10	Integer	0 – 2000	ppm	Gauge & SuperChart: Intensitas gas amonia (MQ-135).
9	Priority Level	V11	Integer	0 – 3	-	Value Display: Scale the urgency of waste handling.
10	Waste Type	V12	String	-	-	Label: Automatic classification (Organic/Inorganic).
11	Recommendation	V13	String	-	-	Label: Preventive instructions/PPE for officers.
12	Latitude	V20	Double	-	GPS	Widget Map: The point of the latitude coordinate point of the device's location.

13	Longitude	V21	Double	-	GPS	Widget Map: The longitude coordinate point of the device's location.

Appendix 3: Full Code C++ Language Algorithm on Arduino IDE

Link: https://github.com/Moechhh/BINSAI_RESEARCH/blob/main/src/main.cpp

Appendix 4: Documentation Figure

GitHub Documentation

Repository link: https://github.com/Moechhh/BINSAI_RESEARCH.git

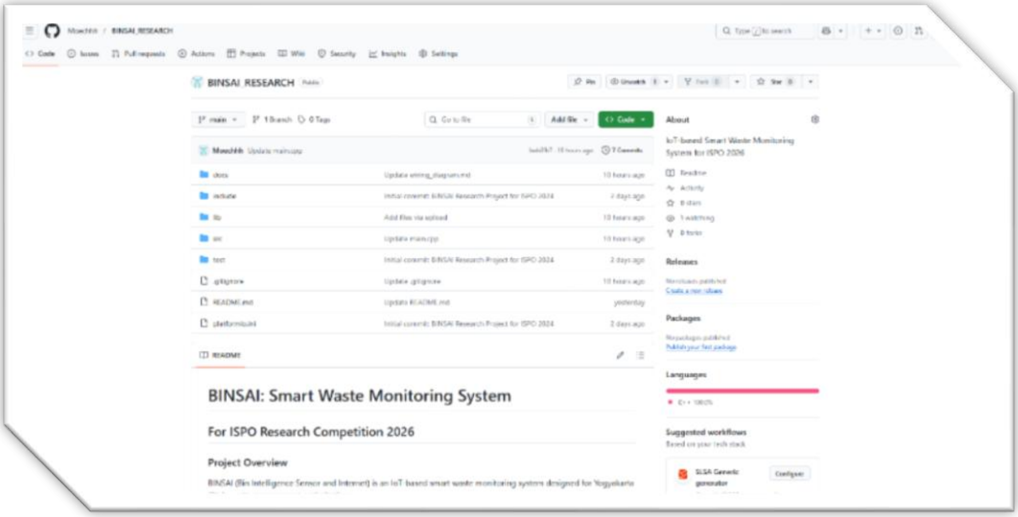

Figure 7: GitHub Dashboard

(Source: Researcher's Personal Documentation)

Figure Preliminary Assembly Drawings

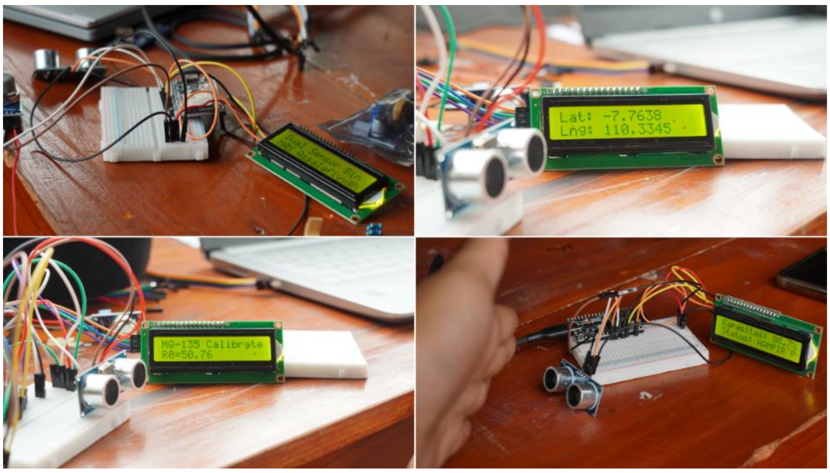

Figure 8: Assembly and Initial Testing on the BINSAI Module

(Source: Researcher's Personal Documentation)

The test series in Figure 8 above shows the system verification process which includes:

1. (a) Interface Initialization Test (Top Left): Verify the display opening on the I2C LCD to ensure the I2C communication line and power supply to the display are operating correctly when the device is first turned on.

2. (b) GPS Spatial Verification (Top Right): Testing of the NEO-6M GPS module in acquiring satellite signals to obtain precise latitude and longitude coordinates at the research site.
3. (c) MQ-135 Dynamic Calibration (Bottom Left): The process of determining the R0 value (sensor resistance in clean air) to ensure the accuracy of the ammonia gas PPM reading to avoid reading errors due to initial environmental conditions.
4. (d) Capacity Accuracy Test (Bottom Right): Simulation of distance measurement against objects to validate the distance to percentage conversion algorithm, ensuring the status displayed on the LCD corresponds to the physical condition of the body occupancy.

Figure of Sent SMS Format

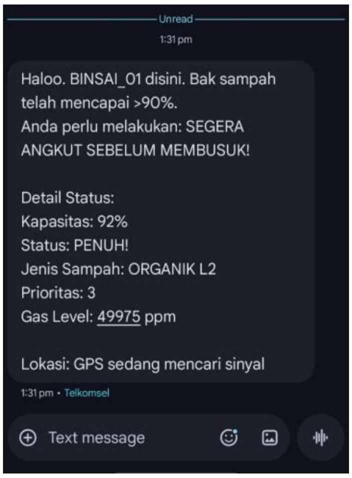

Figure 9: Format of Messages Sent through the Blynk Mobile Application on the BINSAI System

(Source: Researcher's Personal Documentation)

Figure of Modular Smart Bin

Figure 10: Modularization of BINSAI by compacting in enclosure

(Source: Researcher's Personal Documentation)

Component Integration Drawings

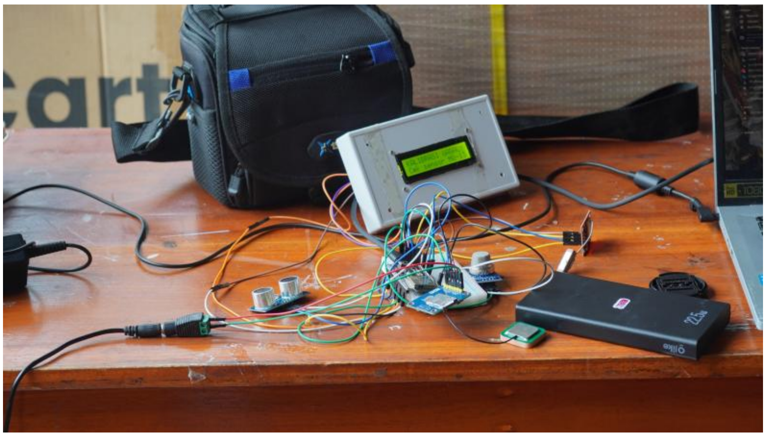

Figure 11: Integration Between Components

(Source: Researcher's Personal Documentation)

MQ-135 Sensor Testing Drawings

Figure 12: Acquisition of ADC (Analog-to-Digital Converter) as a Reference to PPM Value

(Source: Researcher's Personal Documentation)

Based on Figure 12, the following results are obtained.

Visual Analysis of Empirical Testing.

1. Figure A top left (Clean Air Baseline): Shows the initialization stage where the sensor is exposed to clean air (clean air phase). The data showed a stable ADC value at 0 for the initial 14 seconds, which confirmed that the sensor did not detect ammonia (NH3) contaminants above the background threshold.
2. Figure B top right (Real-Time Data Transmission): This is a Serial Monitor documentation that captures the kinetics of rising gas levels as the sensor begins to be exposed to organic waste objects. At the 14th second, the ADC value shows an upward trend but has not yet reached the peak point (120), representing the transition phase of gas diffusion to the sensor surface.

3. Figure C bottom left (Sensor and Pollutant Interactions): Shows the MQ-135 device placed proximal on top of rice that has been decomposed for 3 days. This direct exposure triggers a reduction reaction on the surface of the sensor semiconductor material due to gas emissions from microbial activity.
4. Figure D bottom right (Final Result Validation): The final stage of the test where the system successfully achieves data saturation at the ADC value ≥120 in the last 10 seconds of the test. This data becomes the final basis for the regression model to classify objects as advanced organic waste (Organic Level 2).

NEO-6M GPS Module Testing

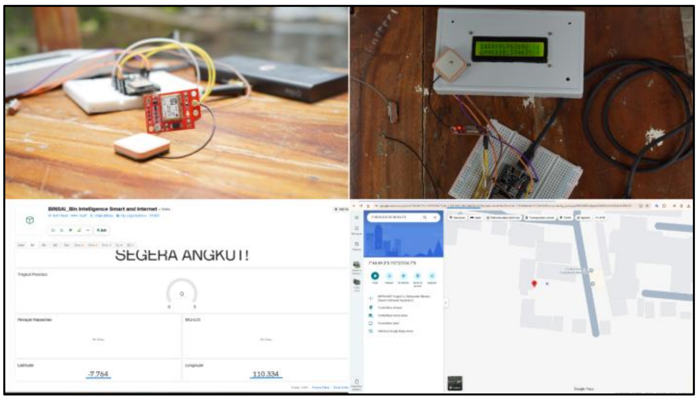

Figure 13: NEO-6M GPS Testing

(Source: Researcher's Personal Documentation)

Figure B (top right) and the Google Maps reference on the laptop, Figure D (bottom right), then the calculation of the percentage of coordinate accuracy that has been described in 4.3.2 GPS and GSM Module Testing is obtained.

Appendix 5: Waste Type Indication Threshold Table

Table 4. MQ-135 Sensor-Based Waste Type Indication Detection Threshold

Conditions	BINSAI (PPM)	Scientific Reference (PPM)	Source
Clean/Normal Air	0 - 199	< 250 - 350	WHO & EPA: Background levels of CO_2‹ in the air are typically 350-400 ppm. MQ-135 often shows low values (0-200) after RZero calibration in clean air.
Inorganic / Light Odor	200 - 449	350 - 600	Srivastava et al. (2017): Indoor air or areas with little pollution/light organic gases are in this range.
Organic (Starting to Rot)	450 - 800	> 600 - 1000	Karthi & Sangeetha (2020): Setting >700 ppm as an indicator of the presence of methane/ammonia gas from wet garbage piles.
Critical (High Rot)	> 800	> 1000	Hanwei Electronics datasheet: MQ-135 has a high sensitivity of up to 1000 ppm. A value of >800 indicates a concentrated concentration of hazardous gases.

Appendix 6 : Activity Agenda Matrix

Activities	**Moon... Week to...**																			
	September				**October**				**November**				**December**				**January**			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Discuss research ideas																				
Looking for literature studies																				
Problem survey																				
Fixation of research titles																				
Creation of research proposals																				
Preparation of research tools and materials																				
Component collection																				
Manufacturing																				
Application																				
Testing																				
Testing																				
Testing																				
Initial data collection																				
Advanced test																				
Data analysis and interpretation of results																				
Research																				
Preparation of the final report																				