DEVELOPMENT OF AN IOT-BASED SMART WASTE MANAGEMENT WEB APPLICATION WITH A SPATIAL MONITORING DASHBOARD

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Abstract– Increasing urban waste volumes create logistical hurdles for the Regional Technical Implementation Unit (UPTD) of Waste Services in Sleman Regency. Currently, truck fleets operate on static schedules without real-time capacity data, causing severe fuel inefficiencies. To resolve this, the study designed an Internet of Things (IoT) smart waste management system integrated with a spatial dashboard using the Waterfall model. An ESP32 microcontroller and HC-SR04 ultrasonic sensor were wired to track available container space. This telemetry is transmitted to a cloud server and displayed instantly on a digital map. Testing involved 10 participants ranging from truck drivers to managers at UPTD Sleman. Evaluation results showed the sensor achieved 97.2% accuracy (2.8% error) with a rapid data transmission time of 7.46 seconds. User Acceptance Testing (UAT) and black-box assessments recorded a functional success rate exceeding 95%. During simulation, the smart routing feature successfully reduced the fleet's daily travel distance from 25 kilometers to 12 kilometers. This logistical optimization directly lowered monthly diesel fuel consumption by 52 percent, dropping from 150 liters to 72 liters.

Keywords: Internet of Things, Spatial Dashboard, Smart Waste Management, Route Optimization, Fuel Efficiency

1. INTRODUCTION

The rising volume of solid waste in urban areas, driven by rapid urbanization, presents complex logistical and sanitation challenges for local waste management agencies. This issue is acutely faced by the Sleman Regency Waste Management Technical Implementation Unit (UPTD), which currently relies on conventional waste collection methods. Truck dispatch schedules are static and tied to fixed routes, lacking any basis in actual, real-time waste volume data from the field. Consequently, the fleet often incurs unnecessary fuel costs and wastes operational time visiting collection points that are not yet full, or are even completely empty. Conversely, waste frequently accumulates beyond container capacity in other areas that happen to fall outside the day's priority schedule. Unless these logistical inaccuracies and routing inefficiencies are addressed through appropriate technological interventions, the local government will continue to face significant operational budget waste and shortened vehicle maintenance cycles, while the quality of public sanitation experienced by the community will directly decline.

In the context of academic research and engineering, the concept of digitizing municipal waste management systems has been extensively studied from various perspectives. Previous research by [1] successfully developed an Internet of Things (IoT)-based information system to minimize collection frequency; however, the system focused primarily on monitoring waste levels and lacked intelligent scheduling algorithms for dynamic fleet route optimization. Another study by [2] focused on designing an early warning system for household waste but relied solely on local indicators, such as buzzer or LED notifications, without integrating a centralized Geographic Information System (GIS) to guide drivers in the field. From a software perspective, research by [3] utilized a visual dashboard to map the distribution of waste composition at a landfill site. Similarly, [4] developed an IoT-based smart monitoring application to evaluate waste container capacity in real-time; however, a major drawback was the reliance on manual data input by operators, thereby undermining the system's autonomous nature. Meanwhile, the centralized web-based capacity notification system developed by [5] modernized traditional SMS reporting methods but remained limited to displaying threshold alerts, lacking the artificial intelligence needed to recommend the most efficient collection routes. More broadly, a comprehensive literature review on Smart Waste Management concepts by [6] and research on spatial analysis using GIS by [7] underscore that geospatial tracking is a crucial pillar of smart cities; yet, these studies have largely focused on theoretical frameworks and static mapping rather than on applied, end-to-end architectures spanning from edge devices to web portals.

Based on the aforementioned literature review, a critical research gap was identified: the lack of a comprehensive and cost-effective integrated system design combining autonomous IoT devices at collection points, cloud-managed database infrastructure, interactive web-based spatial visualization, and routing capabilities into a seamless platform. To address this issue, this research aims to design and build a Smart Waste Management system that effectively bridges this technological gap. At the hardware level, the sensing instrumentation combines the reliability of the HC-SR04 ultrasonic sensor and the NodeMCU ESP32 microcontroller to precisely measure the container's remaining capacity. This telemetry data is periodically transmitted to a Supabase cloud database infrastructure for real-time visualization on a web-based spatial dashboard developed using React.js. The dashboard interface is designed not merely to display passive data but to automatically execute smart routing functions; it selects and maps routes to Temporary Waste Collection Points (TPS) identified as critical priorities (capacity >70%), thereby eliminating unnecessary fleet visits to locations that do not require service.

The primary contribution of this research lies not only in expanding the applied informatics literature by demonstrating that modern real-time REST API architectures can integrate IoT edge devices with precise, low-cost geospatial tracking, but also in offering tangible practical benefits to local government institutions. In practical terms, the implementation of this intelligent system is estimated to significantly reduce fleet travel distances; this, in turn, positively impacts operational cost efficiency (specifically fuel consumption) and mitigates carbon dioxide emissions from the urban logistics sector, a factor highlighted in route optimization studies such as [8]. A comprehensive analysis of system durability and reliability, covering everything from sensor reading error rates and wireless transmission latency to an objective assessment of device usability from the perspective of operational staff, will be detailed in depth within the results and discussion section.

2. RESEARCH METHODS

2.1 Research Framework and Stages

The development process for this intelligent system adopts the Waterfall software engineering method, based on the Generic Process Framework [9]. This linear method was selected due to the need for rigorous oversight during each hardware design phase, as mid-stream specification changes could not be tolerated. System testing involved independent variables—specifically the implementation of a Smart Waste Management architecture, the use of HC-SR04 sensors and ESP32 modules, and the integration of a spatial dashboard—while the dependent variable was the operational efficiency of the UPTD sanitation fleet. The research began with an analysis of fleet fuel wastage issues through field observations at the Sleman Regency UPTD for Waste Management Services. These observations were essential for formulating project success indicators, which included sensor distance reading accuracy, latency threshold determination, and validation of application interface synchronization.

The physical infrastructure of the Internet of Things (IoT) device was assembled, calibrated, and packaged to generate data payloads in JSON format, transmitting them to a backend database server via a REST API. On the client-facing side, the application was implemented as a functional web dashboard featuring real-time geolocation mapping capabilities. The feasibility of the final product was comprehensively validated using modern software engineering standards [9]. User Acceptance Testing (UAT) was conducted with 10 participants selected via purposive sampling; this group specifically comprised UPTD management personnel, system monitoring administrators, and logistics truck drivers. The testing combined two evaluation metrics: functional black-box interaction testing and the recording of qualitative user observations.

Figure 1. Research Steps

2.2 System Architecture and Design

The architecture of this waste management system is hierarchically divided into three primary operational layers: the Perception Layer, the Network Layer, and the Application Layer [6]. At the lowest level—the Perception Layer—an HC-SR04 ultrasonic sensor module is installed facing directly downward toward the bottom of the waste container (top-down orientation) to minimize sound wave propagation interference. This sensor is electronically integrated with a NodeMCU ESP32 microcontroller [10]. The acoustic wave reflection time (echo) is mathematically converted into a volumetric capacity percentage ranging from 0% to 100%.

At the Network Layer, data transmission is executed wirelessly via the ESP32's internal Wi-Fi module using an HTTP POST scenario directed at a REST API service [11] provided by the PostgreSQL-based BaaS platform, Supabase [12]. This cloud infrastructure was selected to eliminate the maintenance burden associated with on-premise server infrastructure for local government agencies. At the Application Layer, a spatial monitoring dashboard was developed entirely using the React.js user interface library. To prevent potential server network load spikes caused by repetitive traditional polling routines, the client-side communication scheme intelligently adopts the WebSockets communication protocol (Supabase Realtime). This architectural decision ensures that changes in waste capacity percentage indicators and shifts in geographic color markers on the operator's browser display are updated instantaneously, in sync with the telemetry data transmitted from the field sensors.

2.3 System Testing Scenarios

The functional evaluation was rigorously structured according to the software testing hierarchy standard [9] and comprised three primary scenarios. The first experimental scenario focused on the physical hardware by calibrating the accuracy of the HC-SR04 sensor against a physical ruler to determine the error rate. The second scenario aimed to measure transmission network reliability by recording the latency—the time elapsed between the sensor detecting a change in physical waste elevation and the corresponding interface update on the dashboard—with a maximum tolerance threshold of 30 seconds. The third scenario evaluated core functionality through Black-Box Testing of authentication features and mapping logic, followed by User Acceptance Test (UAT) validation [13] involving Sleman UPTD staff to assess the objectivity of the interface.

3. RESULT AND DISCUSSION

The development of this innovative system prototype focuses on two primary functional architectural domains: the assembly of physical environment detection modules onto waste containers and the deployment of a web-based logistics management monitoring portal [14]. The fully integrated system is then holistically evaluated to validate mechanical reliability, network stability, and the operational impact on logistics for the Sleman Waste Management Service Unit (UPTD) [15].

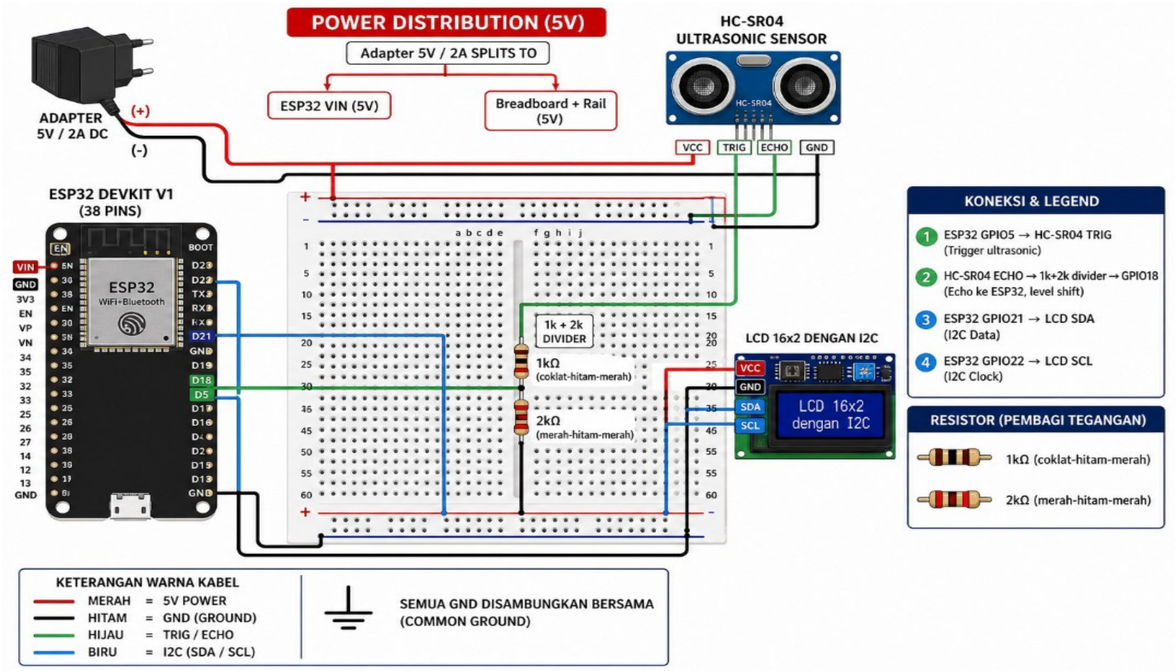


Figure 2. Design of the system

3.1 Hardware and Software Implementation

The electronic circuitry at the edge node level is implemented by mounting the HC-SR04 ultrasonic sensor module vertically on the underside of the waste bin lid. This positioning is crucial to prevent asymmetrical sound wave reflections often caused by uneven waste piles [16]. The system's core, an ESP32 microcontroller, runs firmware that precisely measures the duration of the ultrasonic echo and proportionally converts it into the percentage of remaining space [1]. Integrating this microcontroller with the ultrasonic sensor for autonomous bin capacity calculation has proven highly efficient in recent smart waste management system prototype designs [17]. The device also features a physical Liquid Crystal Display (LCD) to facilitate visual inspection by field technicians. Given that the HC-SR04 sensor operates at 5 Volts while the ESP32's internal logic ports accept a maximum signal of 3.3 Volts, a voltage-lowering circuit utilizing 1 kOhm and 2 kOhm resistors in series was incorporated. This voltage modification is essential to step down the echo signal level to a safe 3.33 Volts, thereby preventing permanent damage to the microcontroller's GPIO pin circuitry [18].

3.2 Database Architecture and Network Security

At the backend layer, the Supabase platform, built upon the PostgreSQL relational foundation [19], is utilized to robustly manage the data architecture schema [20]. Its centralized storage structure is highly optimized into three table types: a `bins` table for recording physical container dimensions and geographic coordinates; a `readings` table for archiving time-series data on waste metrics; and an `alerts` table for logging critical capacity threshold warnings. Microcontroller telemetry data is formatted using JSON structures to ensure minimal internet data consumption. The entire data transmission pathway is secured via API Key authentication and PostgreSQL Row-Level Security (RLS) authorization to thwart potential man-in-the-middle attacks [21].

3.3 Interactive Web Interface Development

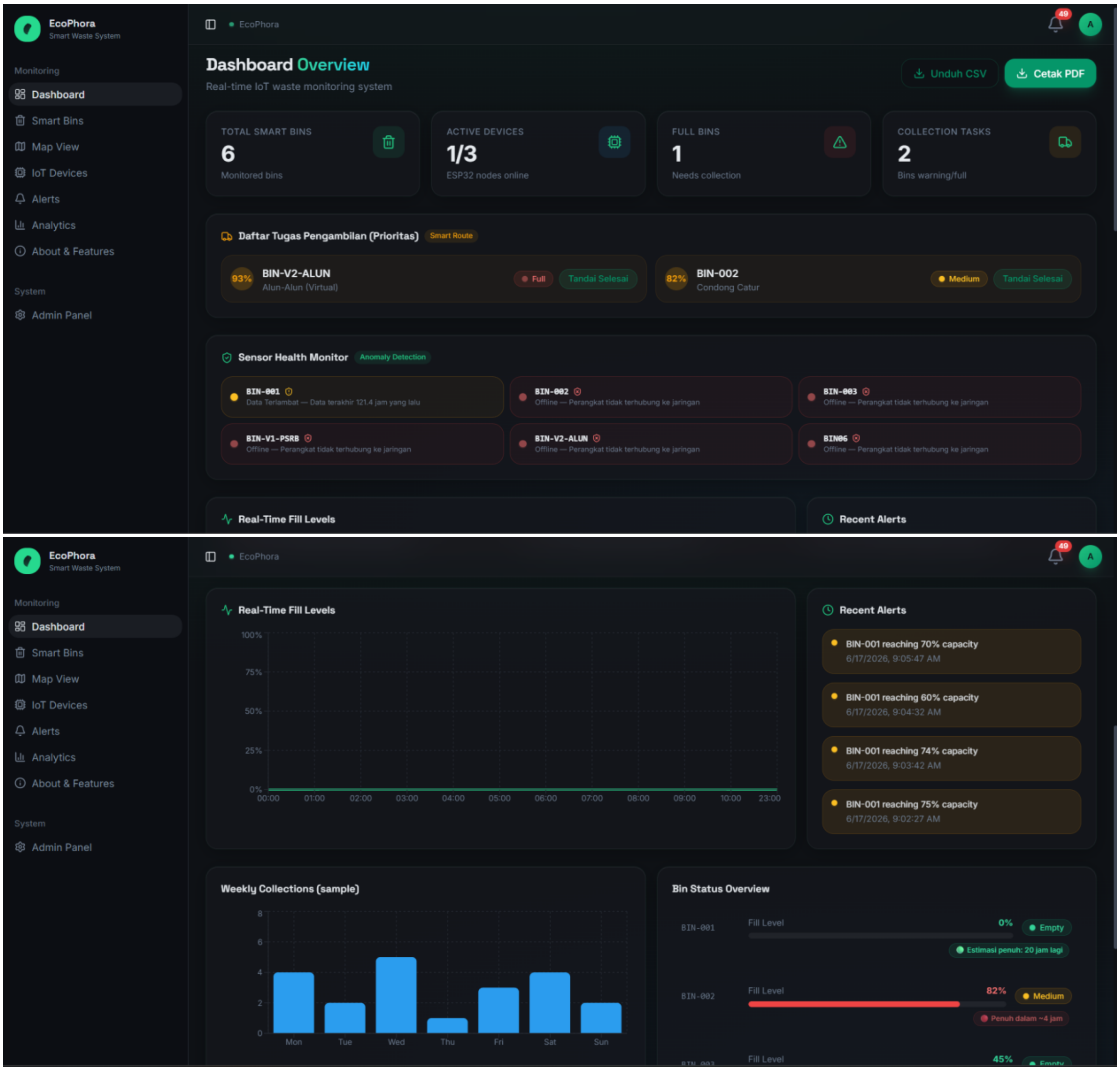


Figure 3. Dashboard Overview Page

On the client-side layer, the web interface is built entirely using the React.js library. React's Virtual DOM approach offers a fundamental advantage in rendering optimization, allowing the waste level percentage indicator to update instantly without requiring a full page reload [22]. City topology mapping utilizes the open-source Leaflet library, with coordinate point colors dynamically updated via the Supabase Realtime WebSockets protocol [23]. The dashboard portal features an aesthetically pleasing navigation hierarchy, beginning with an Authentication Page that serves as the secure gateway for internal credentials [24].

A distinctive feature of the system is its interactive Map View page. This page visualizes all active waste container locations using intuitive color-coded indicators: green for safe status (below 50%), yellow for a warning state (50–70%), and red to represent critical capacity (above 70%). Notably, the interactive map includes an automated route optimization function that algorithmically plots the shortest path along roadways to visit only those locations with critical status [8]. Finally, the Admin Panel module provides an interactive form interface allowing UPTD management to register new sensor units or reposition waste collection point coordinates without interacting with raw code [22].

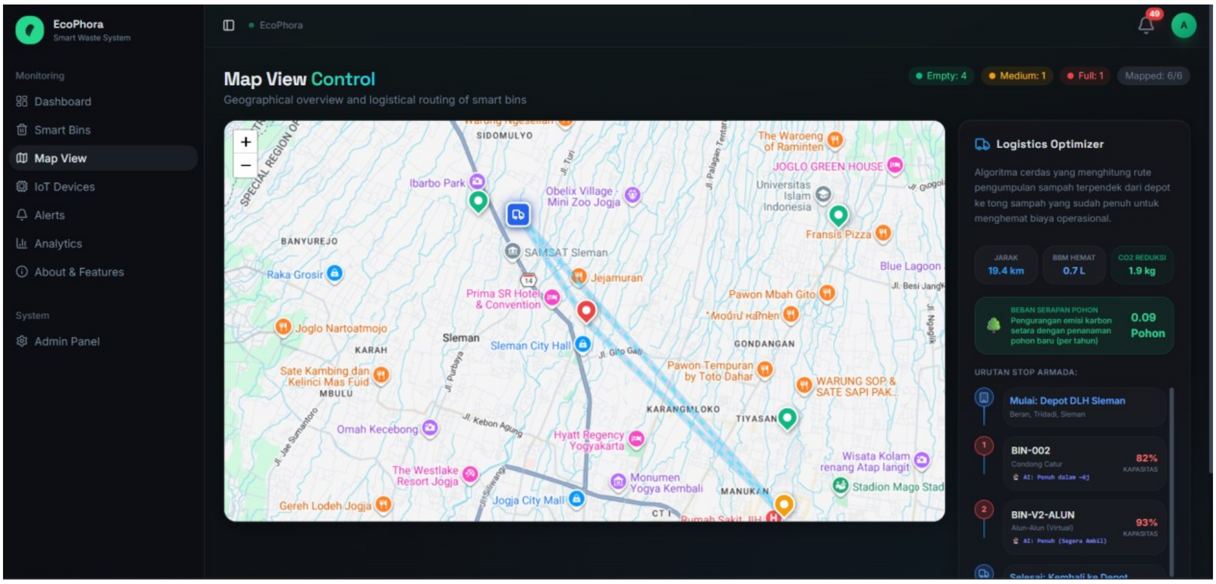


Figure 4. Map View and Route Optimization Page

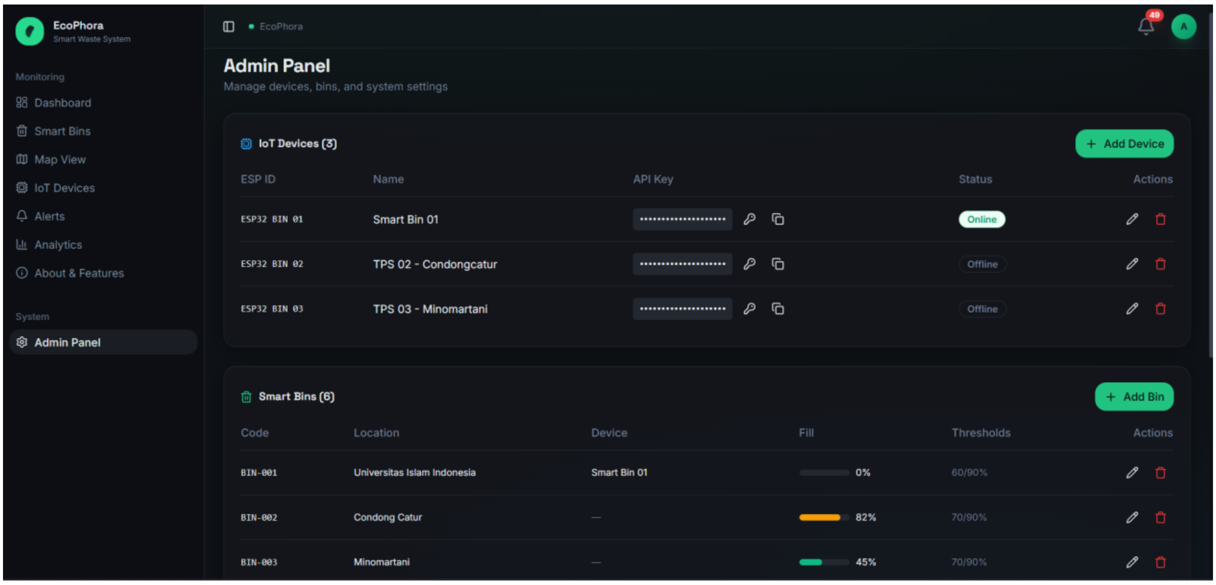


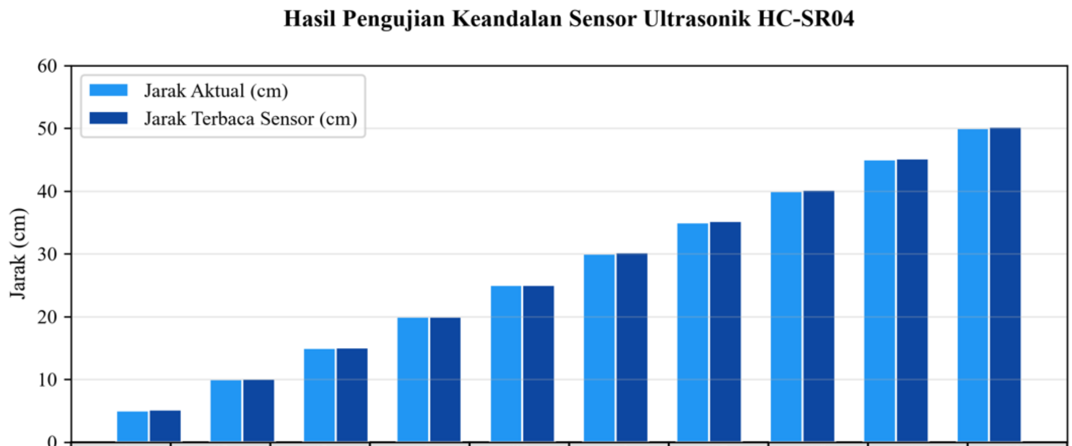
Figure 5. Admin Panel Page

3.4 Sensor Calibration and Accuracy Scenarios

Calibration validation testing for the HC-SR04 sensor component was conducted by recording the difference in distance measurements to a physical obstacle, varied from 5 cm up to a limit of 50 cm. The calculated values were compared against manual measurements to assess precision correlation. Based on the test results summarized in the Sensor Test Graph, the fluctuation in microcontroller readings demonstrated a consistent margin within the millimeter resolution range—specifically, a deviation of 0.0 cm to a maximum of 0.2 cm. Error rates and sensor accuracy were calculated using equations (1) and (2).

$$\text{Capacity (\%)} = ((\text{Total Height} - \text{Measurement Distance}) / \text{Total Height}) \times 100\%$$
$$\text{Error (\%)} = |\,(\text{Measured Value} - \text{Actual Value}) / \text{Actual Value}\,| \times 100\%$$
$$\text{Accuracy (\%)} = 100\% - \text{Error (\%)}$$

Computational statistical analysis confirms that the average sensor performance accuracy was maintained at 97.2%, with a minimal error rate of 2.8%. This remarkably low margin of error serves as authentic proof that the remote sensing instrument has achieved stable operational precision. The validity of these accurate readings prevents data anomalies—such as false alarms—that could otherwise mislead logistics truck drivers during daily navigation decision-making [16].



	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Jarak Aktual (cm)	5	10	15	20	25	30	35	40	45	50
Jarak Terbaca (cm)	5.2	10.1	15.1	20	25	30.2	35.2	40.2	45.2	50.2
Selisih / Error (cm)	0.2	0.1	0.1	0	0	0.2	0.2	0.2	0.2	0.2
Persentase Error	4%	2%	2%	0%	0%	4%	4%	4%	4%	4%
Status	Valid	Valid	Valid	Valid	Valid	Valid	Valid	Valid	Valid	Valid

Figure 6. Sensor Test Results

3.5 Network Synchronization Latency Analysis

Network quality of service (QoS) resilience testing aimed to confirm that the execution of asynchronous transmission updates was as fast as the real-time interface constraints. The computational latency index was calculated using a stopwatch from the first pulse of the sensor detecting the volume shift of waste within the container until the visual update of the percentage and color of the coordinate marker was recorded on the central administrator's web browser page.

Through repeated transmission load testing, system recording results showed that the telemetry assimilation process from the microcontroller endpoint to the web screen took an average of 7.46 seconds. This impressive track record of wireless transmission performance objectively confirmed its safety and met the quality standards. This 7.46-second figure significantly exceeds the maximum synchronization tolerance threshold for conventional early warning communication systems, which, in theory, ideally requires a 30-second minimum for IoT networks [25]. This latency response speed is crucial for operator emergency responsiveness.

3.6 Software System Functional Testing

The validity of the administrative web application code was verified using a black-box testing approach to ensure the integrity of user interactions and freedom from error-induced interruptions. The testing scope covered five key operational scenarios: (1) validation of encryption for the login page authentication mechanism; (2) simulation of CRUD operations and coordinate mapping pin adjustments (Map Picker tool); (3) stability testing of bidirectional data transmission via the WebSocket protocol; (4) activation of visual alerts for critical status conditions (triggered when capacity exceeds a 90% threshold); and (5) computational testing of polygon rendering for smart logistics route mapping. According to the developer's test matrix report, the React JS interface achieved a perfect 100% execution success rate across all scenario parameters, with no instances of memory leakage detected.

Table 1. Black-Box Testing Results

No	Test Scenarios	Expected Results	Test Results	Conclusion
A	Authentication Functionality			
1	Login with validated credentials	Access granted and redirected to the main dashboard	Compliant	Successful

B	Route Mapping and Optimization			
2	Shifting TPS coordinate pins on the Admin page	Marker position updates precisely on the main map	Compliant	Successful
3	Execution of the Smart Routing recommendation feature	Route line maps out polling stations (TPS) with red (critical) status	Compliant	Successful
C	Real-Time Data Synchronization			
4	Changes in sensor distance within the physical container	Percentage indicator on the web updates instantly	Compliant	Successful
5	Triggering of capacity limit alerts (>70%)	Polling station color changes to red & triggers an alert log	Compliant	Successful

3.7 User Experience Evaluation

The system was evaluated through a User Acceptance Test (UAT) survey involving operational staff. Qualitative data was gathered using a questionnaire employing a 1-to-5 Likert scale. This field survey involved ten participants representing various levels within the Sleman Waste Management Service Unit (UPTD), including unit leadership, system administrators, and fleet drivers.

Tabulation of the questionnaire responses revealed an overwhelming consensus regarding satisfaction. The system achieved an aggregate score of 95%, earning an "Excellent" rating. This high level of technology acceptance demonstrates the staff's unanimous opinion that the system's dashboard interface is highly user-friendly for beginners. Regarding strategic functionality, users agreed that the dynamic map integration significantly assists the institution in formulating more tactical strategies to optimize daily operational schedules for truck fleet dispatch [13].

3.8 Operational Impact and Logistics Efficiency

The reliability of this synchronous IoT data assimilation transmission directly enables a breakthrough in logistics cost savings through dynamic fleet route optimization. A review of the conventional scheduling practices at UPTD Sleman prior to the system's implementation reveals that the institution was previously constrained by the necessity of executing static transport routes based on "blind navigation." This conventional routine inadvertently burdened physical inspection cycles, forcing massive transport trucks to traverse the entire radius of waste collection points (TPS) and cover a minimum daily distance of 25 kilometers [1][7]. The fleet covered these distances passively, without accounting for variables such as the percentage of empty space or actual waste volume density.

Following the activation of a smart standby capacity threshold filter—set at 70% via the central application dashboard—the digital map automation system instantly identified and excluded waste collection points (TPS) with low fill volumes (indicated by green and yellow statuses). Data from field route trials showed that the system's spatial intelligence (powered by Leaflet) directed the fleet to focus exclusively on four specific waste collection sites that had reached the critical emergency warning threshold. This prioritization strategy achieved a significant reduction in the fleet's operational travel distance; specifically, the previous consistent route length of 25 kilometers was slashed to just 12 kilometers per session.

Furthermore, the reduction in the operational travel distance of these diesel-powered heavy commercial trucks has transformed their role into a direct contribution to the institution's operational economies of scale. Analysis of fleet fuel consumption data provides empirical confirmation that the reduction in travel distance corresponds proportionally to a decrease in the nominal cost of monthly logistics fuel supplies. Whereas the budget initially projected a consumption of 150 liters of diesel, cutting the travel distance from 25 km to 12 km successfully reduced institutional fuel usage to a minimum of just 72 liters per 30-day cycle.

In terms of logistics mathematics, this autonomous, intelligent routing system has demonstrated an exponential reduction in transportation costs, achieving an efficiency saving of 52% [7]. Beyond the phenomenal improvement in the commercial fuel accounting balance, eliminating excessive engine operation serves as a concrete policy solution for urban management, supporting global green initiatives and curbing carbon dioxide emissions in the Sleman Regency area [6][8].

4. CONCLUSION

This research successfully designed and implemented an integrated Smart Waste Management system combining IoT sensing components, specifically the ESP32 and HC-SR04, within the physical infrastructure, alongside a web-based spatial monitoring dashboard interface. The system proved effective in resolving inefficiencies associated with static fleet routing methods in the operational environment of the Sleman Regency Waste Management Service Unit (UPTD). Technical testing demonstrated high hardware precision, achieving 97.2% calibration accuracy with a 2.8% margin of error, supported by robust asynchronous connectivity and an ultra-fast average latency of 7.46 seconds. On the software side, the system achieved a 99% operational success rate in black-box testing and secured a 95% acceptance score from UPTD staff during the User Acceptance Test (UAT).

The smart fleet routing functionality demonstrated tangible benefits by streamlining the navigation cycle, reducing the daily conventional route from a 25-kilometer circuit to a far more efficient, targeted 12-kilometer path. This optimization, driven by real-time data filtering, curtailed logistics trip frequency, resulting in a concrete 52% reduction in diesel fuel expenditure, lowering monthly consumption from 150 liters to 72 liters. Beyond restoring economic efficiency to the government agency's budget, this mechanism simultaneously mitigates the environmental impact of carbon emissions generated by heavy transport vehicles in the urban atmosphere. Regarding future development, it is recommended that the field sensing system be enhanced by integrating a standalone cellular transmission connectivity module, such as a SIM800L GPRS telemetry device, so that the deployment of the outdoor IoT sensor network is not constrained by the availability of commercial local Wi-Fi internet infrastructure.

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