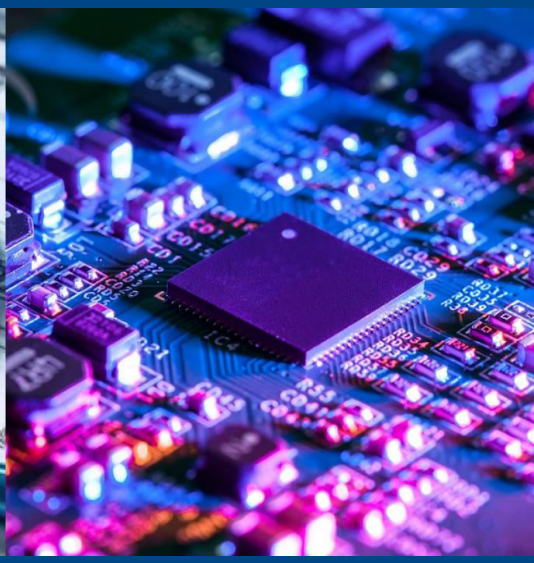
ISSN: 2582-7219





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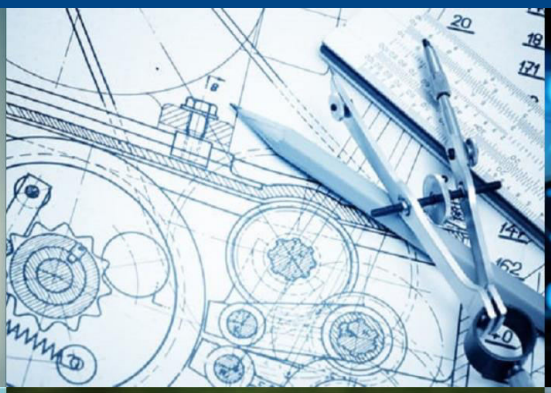

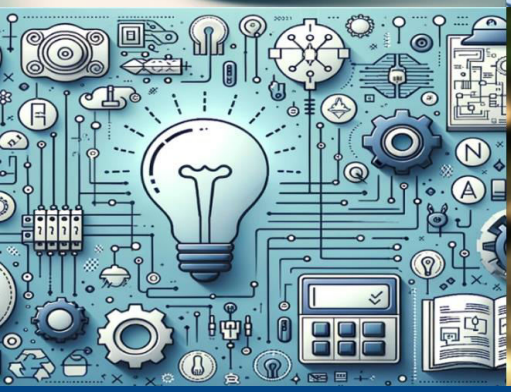

Impact Factor: 9.864

Volume 9, Issue 5, May 2026

© 2026 IJMRSET | Volume 9, Issue 5, May 2026| DOI:10.15680/IJMRSET.2026.0905079

ISSN: 2582-7219 | www.ijmrset.com | Impact Factor: 9.864| ESTD Year: 2018|

International Journal of Multidisciplinary Research in Science, Engineering and Technology (IJMRSET)

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)

Hybrid-Based Smart Waste Collection and Monitoring System

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ABSTRACT: The Hybrid-Based Smart Waste Collection and Monitoring System was developed for Barangay Lininti-an to improve urban waste management. Smart bins equipped with ultrasonic sensors and ESP32 microcontrollers transmit real-time fill-level data to a web dashboard and mobile application. Threshold-based alerts support condition-based collection instead of fixed schedules. The system was evaluated using ISO/IEC 25010 standards, showing high scores in functional suitability, reliability, usability, and security. Results indicate that the prototype is an efficient, scalable, and cost-effective solution that enhances operational efficiency, reduces unnecessary trips, and supports cleaner and more sustainable barangay waste management.

KEYWORDS: Smart waste management, Ultrasonic sensors, ESP32 microcontroller, Hybrid monitoring system, ISO/IEC 25010

I. INTRODUCTION

Solid waste management is crucial for environmental protection, public health, and sustainable community development. In many developing urban areas, including barangays, traditional waste collection relies on fixed schedules that do not reflect the actual status of waste containers. This often leads to overflowing bins, unpleasant surroundings, and potential health risks. Limited resources, inadequate infrastructure, and inconsistent policy implementation further worsen these challenges.

To address these issues, Hybrid-Based Smart Waste Collection and Monitoring System using sensors, microcontrollers, and data-driven platforms have emerged as promising solutions. However, most implementations focus on large cities with advanced infrastructure. This study presents a designed for Barangay Lininti-an, Cantilan, Surigao del Sur. The system integrates sensor-based smart bins, a web-based dashboard, and a mobile application to enable real-time monitoring, threshold-based alerts, and optimized waste-collection operations at the barangay.

II. LITERATURE SURVEY

Foreign literature shows that modern waste management increasingly adopts data-driven optimization and intelligent systems. Yu et al. (2022) highlighted that models such as the Regional Location Routing Problem (RLRP) and Multi-Depot RLRP, when combined with hybrid algorithms such as genetic algorithms and simulated annealing, significantly improve routing efficiency and reduce operational costs. Cha et al. (2022) introduced hybrid machine learning models (e.g., CATPCA-SVMR) that enhance predictive accuracy for dynamic, limited datasets, demonstrating the value of predictive analytics for planning waste collection.

Fatovatikhah et al. (2024) integrated deep learning and machine learning (LSTM and SVM) to forecast waste generation in disaster scenarios, highlighting the need for resilient, adaptive systems. Silva et al. (2024) showed that combining optimization algorithms with hybrid vehicle systems can reduce both costs and CO_2 emissions, aligning waste collection with environmental sustainability goals. Kannan (2024) conceptualized Smart Waste Management 4.0, integrating Industry 4.0 technologies, automation, and interconnected systems, but such approaches typically assume robust infrastructure.

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Local literature reveals persistent implementation gaps in the Philippines. Ciudad et al. (2022) found that public indifference, insufficient training, and a lack of protective equipment hinder the effective implementation of Republic Act 9003. Gamao (2023) reported that administrative and procedural constraints limit proper handling and storage of waste across coastal, upland, and lowland areas. Angeles-Agdeppa et al. (2023) demonstrated that analyzing household waste patterns supports targeted strategies to reduce waste and improve public health.

Technological innovations at the local level are emerging. Claire et al. (2024) developed AI-powered smart trash bins using YOLO-based object recognition, significantly improving classification accuracy and user compliance. Miguel et al. (2023) designed a sensor-based waste-monitoring system using Time-of-Flight sensors and ESP32 microcontrollers, demonstrating that real-time fill-level detection and communication can enhance collection efficiency and promote sustainable practices.

Across foreign and local studies, a consistent theme emerges, integrating sensors, data analytics, and hybrid monitoring platforms can shift waste management from static, schedule-based operations to dynamic, demand-driven systems. However, there is a clear gap in context-appropriate solutions for smaller communities with budget constraints, unstable connectivity, and limited technical support, precisely the context of Barangay Lininti-an that this study addresses.

III. METHODOLOGY / APPROACH

Research Design

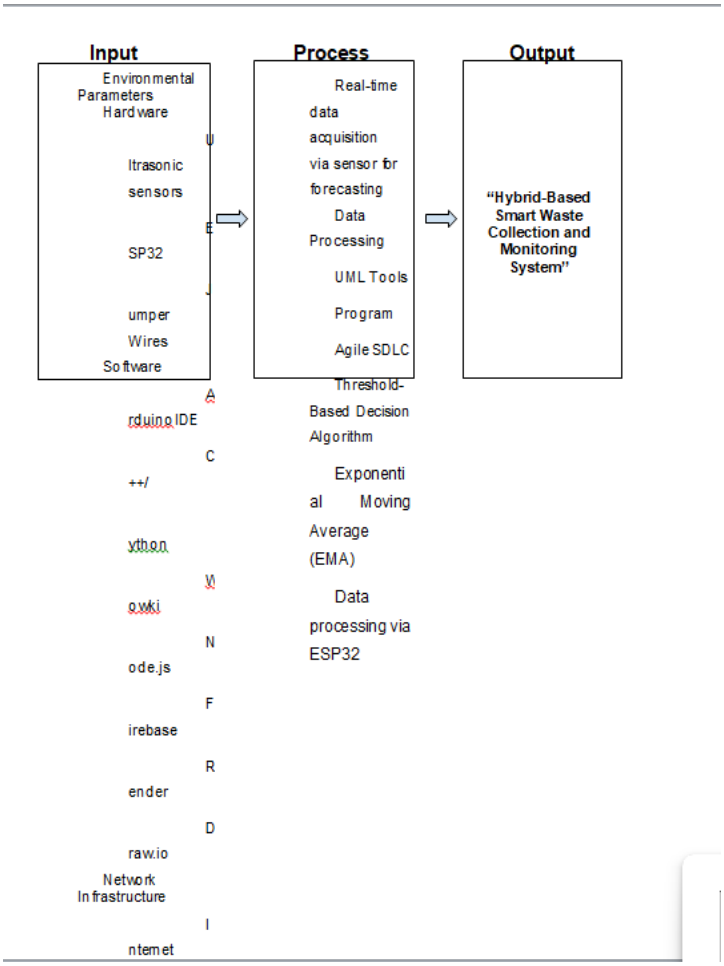

Figure 1.0: IPO Diagram

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The Input-Process-Output (IPO) model, describes a system as a collection of components that work together. The study uses sensor data as input, which the ESP32 microcontroller and the cloud platform process to deliver real-time monitoring and alerts. The integration of both input and process ensures that the system is structured and continuously improves through iterative development.

The system achieves sustainable operation through its integrated input and process system, which provides a data-driven solution that improves efficiency while reducing environmental harm and maintaining urban cleanliness. The system offers scalability and user-friendly operation.

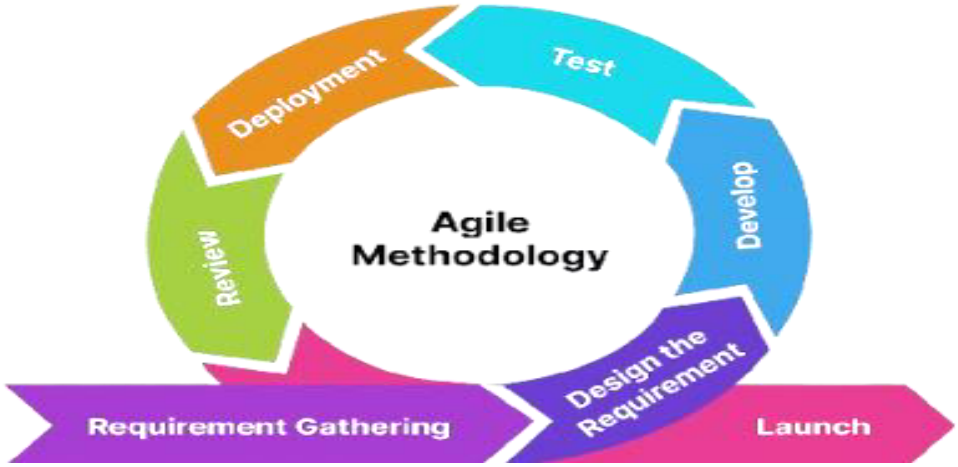

Figure 1.1: Agile SDLC Methodology

The study adopted an Agile Software Development Life Cycle (SDLC) tailored to a hybrid hardware–software system. The research was conducted in Barangay Lininti-an, Cantilan, Surigao del Sur, a developing area with resource-constrained waste management and network instability. Residents, waste collectors, and staff from the Municipal Environment and Natural Resources Office (MENRO) served as respondents. The sample size of 362 participants was determined using Slovin's formula with 95% confidence and a 5% margin of error.

Agile development proceeded through several iterations. The first iteration created a minimal prototype with an ESP32 and an ultrasonic sensor to measure distance and output readings. The second iteration integrated an Exponential Moving Average (EMA) algorithm to smooth sensor noise and established connectivity with Firebase. The third iteration implemented threshold logic and notification delivery. The fourth iteration added hybrid monitoring interfaces: a web dashboard for MENRO administrators and a mobile application for collectors.

Testing and validation spanned multiple level: unit testing of sensor readings and algorithms; integration testing of end-to-end data transmission; functional testing of threshold classification and alerts; and performance testing of latency and responsiveness. The system was evaluated against ISO/IEC 25010 criteria, including functional suitability, reliability, performance efficiency, usability, maintainability, and security.

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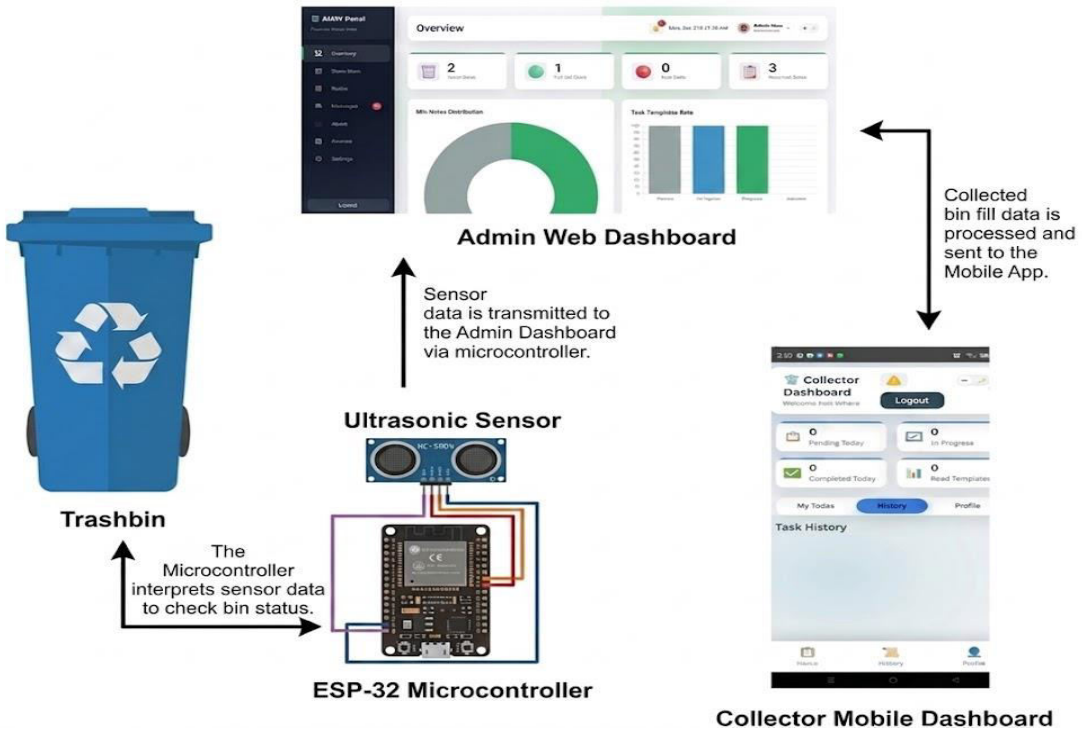

Figure 1.2: Components Diagram

The Hybrid-Based Smart Waste Collection and Monitoring System operates as an integrated ecosystem where an Ultrasonic Sensor (HC-SR04) installed in the bin measures waste levels and sends signals to an ESP32 microcontroller. The ESP32 processes this data and transmits it via its Wi-Fi/Internet Module to a Node.js backend server hosted on Render, which manages API routing and logic. This processed data is then stored in a Firebase Cloud Database, enabling real-time synchronization with the Admin Web Dashboard for centralized management and the Collector Mobile Application for updates.

IV. RESULTS & DISCUSSION

Table 4.6 Overall Summary of Results

Criteria	Average Mean	Average SD	Description
Functionality	4.33	0.79	VGE
Reliability	4.16	0.78	VGE
Usability	4.37	0.77	VGE
Efficiency	4.33	0.78	VGE
Maintainability	4.36	0.77	VGE
Security	4.36	0.79	VGE

To ensure that the system is ready for real-world use, it was tested. Its performance was validated by comparing it against international software quality criteria (ISO/IEC 25010 Standards), and results showed very positive user feedback across all categories evaluating the system.

The system demonstrated high overall performance across all evaluation categories. In terms of Functional Suitability, the system successfully performed all of its main functions and obtained an average mean score of 4.33, with the

accurate performance of the fill level sensors contributing the highest mean score of 4.39. For Operational Reliability, the system received a rating of 4.16, indicating its capability to provide continuous service over extended periods with minimal technological failures, although internet connection issues affected performance, resulting in a lower score of 3.59. User Experience and Usability was the highest-rated category with a mean score of 4.37, as participants found the interface visually appealing and easy to navigate even for first-time or unfamiliar users. Maintainability was rated 4.33, reflecting that the system was simple to troubleshoot and upgrade, while the high mean score of 4.39 for identifying and fixing problems suggests strong long-term sustainability. Lastly, Security and Data Protection received a rating of 4.36 due to the implementation of effective data security measures that prevented unauthorized access and ensured the protection of essential operational data.

V. CONCLUSION

The study demonstrates that a Hybrid-Based Smart Waste Collection and Monitoring System can significantly improve waste management operations at the barangay level. By integrating ultrasonic sensors, ESP32 microcontrollers, a cloud-based backend, and hybrid monitoring interfaces, the system delivers real-time bin status information and automated threshold-based alerts. This enables a transition from fixed-schedule collection to condition-based operations, reducing unnecessary trips and enhancing overall efficiency.

Evaluation against ISO/IEC 25010 standards indicates high levels of functional suitability, reliability, usability, maintainability, and security. Users found the platform intuitive and effective for monitoring and managing waste collection tasks. Although the system is currently at the prototype and pilot stage with limited deployment, findings indicate that it is a practical, scalable, and cost-effective solution for resource-constrained communities.

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