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An IoT-Based Intelligent Waste Segregation System with Real-Time Capacity Monitoring

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***Abstract*— Waste management in Indonesia is confronting a critical crisis, marked by the accumulation of 85% of waste in nearly full landfills and persistently low rates of source segregation, particularly in university campus environments. This study presents the development of RecyClean Smart Bin, a prototype IoT-based intelligent waste bin that integrates an ultrasonic sensor for real-time bin capacity monitoring, proximity and capacitive sensors for automatic classification of organic, inorganic, and metallic waste, and a web-based application for remote monitoring. The methodology encompasses hardware–software co-design, firmware programming, system implementation, and functional validation conducted over five days using fifteen representative waste samples. Results indicate excellent ultrasonic sensor accuracy (maximum deviation of 0.6 cm) and an overall sorting success rate of 80% (12 out of 15 samples), with particularly high precision in metallic waste detection. The proposed system offers a practical contribution toward advancing the circular economy and enabling sustainable smart environments.**

***Index Terms*— Capacity Monitoring; IoT; Waste Segregation**

I. INTRODUCTION

Waste management in Indonesia is facing a severe crisis. National data indicate that, of the approximately 68.5 million tons of waste generated annually, the majority (85%) accumulates in landfills that are nearing or have already reached maximum capacity, according to the National Waste Management Information System (SIPSN). Data from the SIPSN, managed by the Ministry of Environment and Forestry (KLHK), show that in 2023 Indonesia generated around 35.9 million tons of waste, with food waste constituting the largest share (41.5%) followed by plastics (18.5%) [1]. Statistical reports covering the last three years (2022–2024) further reveal that plastic and metal waste together account for an average of 20.88% of the total waste composition. In the region under study, annual waste production reaches approximately 862,013 tons, predominantly consisting of plastic bottles and aluminum cans. However, only 60.71% of this waste is successfully processed through formal management systems, while the remainder accumulates in final disposal sites or is discarded illegally in open areas [2]. These conditions underscore the urgent need to strengthen source-level segregation, particularly in university campus environments characterized by high mobility and the generation of highly diverse waste streams.

Inaccurate segregation at the source significantly degrades the quality of recyclable materials and drives up overall management costs. Recent studies have shown that properly sorted waste commands an economic value 4–10 times higher than mixed waste [3]. This evidence reinforces the critical need for accurate, real-time sorting to boost recycling productivity and advance the circular economy, particularly within university campuses. In addition, conventional waste collection systems suffer from notable inefficiencies; it has been reported that up to 40 % of collection trips are made while bins are still not full, resulting in substantial energy wastage and elevated carbon emissions.

A substantial body of prior research has applied information and communication technologies to improve environmental sanitation. These studies encompass IoT-based monitoring of environmental conditions, which plays a vital role in protecting human well-being and preserving ecosystems [4], [5], [6], [7], [8]. Beyond sensor-driven IoT monitoring, information technology has also been deployed through web-based [9] or mobile software applications to support broader environmental cleanliness initiatives [10], [11]. The application most directly addressing the root cause of environmental degradation—waste itself—is the development of smart waste bins and intelligent waste management systems. These solutions utilize IoT technology together with specialized sensors to detect bin fill levels and automatically classify waste types [1], [3], [12].

A growing body of literature has examined innovations in smart waste bins as a means of overcoming the inefficiencies inherent in conventional waste management. Studies [13] and [14] focus on the development of automated, contactless containment prototypes in which an ultrasonic sensor triggers the lid to open automatically for several seconds upon detecting the physical presence of a user. To address the upstream problem of mixed recyclable materials, the system presented in [13] further incorporates capacitive sensors and servo motors to enable autonomous segregation of organic and inorganic waste. This hardware-centric automation approach is consistent with the findings of [15], which underscore that the implementation of segregation technologies is essential for supporting sustainable urban planning practices while simultaneously paving the way for the integration of more advanced intelligent algorithms that can enhance operational scalability in the future.

In the domain of logistics management and remote monitoring, the integration of the Internet of Things (IoT) has proven critical in mitigating waste accumulation caused by lapses in manual inspections. Studies [13] and [16] specifically developed early-warning systems based on NodeMCU microcontrollers that monitor ultrasonic sensor thresholds and promptly dispatch full-capacity notifications to sanitation personnel via the Telegram platform. A more comprehensive monitoring ecosystem was engineered in [17], which not only acquires volume metrics but also calculates waste weight in real time using load cells. In that study, all data transmitted from the ESP32 module is streamed to a Firebase cloud architecture and visualized through a web interface. This functionality effectively provides relevant authorities with a robust data foundation for making precise logistical decisions while substantially minimizing human intervention.

This study addresses the technical challenges in modern waste management by formulating three interrelated research questions. First, it investigates the development of an Internet of Things (IoT)-based automatic waste sorting system capable of detecting and classifying metallic, inorganic, and organic waste with high accuracy and real-time response. Second, the study evaluates the effectiveness of integrating proximity sensors to enhance the precision of metallic waste detection within inorganic waste piles, thereby enabling targeted separation that supports more efficient recycling processes. Finally, it examines the design and implementation of a web-based management application that facilitates remote monitoring of bin capacity. While previous studies [13] and [15] often focus on binary classification or standalone automated bins, this research contributes a novel two-stage sequential sorting architecture. The first stage utilizes inductive proximity for high-precision metallic isolation, while the second stage employs a majority-voting capacitive sensing algorithm to differentiate organic from inorganic waste. Furthermore, unlike [16] which uses simple notification triggers, our system integrates a relational MySQL database for historical trend analysis of bin capacity, providing a data-driven foundation for waste collection logistics.

In alignment with the related studies outlined earlier, the primary objective of this research is to design and implement a prototype of an integrated IoT-enabled smart waste sorting system capable of automatically and precisely segregating waste categories at the point of generation. More specifically, the study aims to validate the reliability of proximity sensor integration as a means of improving the accuracy of metallic waste extraction from inorganic materials, while simultaneously developing a comprehensive web-based information system. This platform is intended to empower stakeholders with real-time bin capacity monitoring and more structured logistics management for waste collection.

The urgency and significance of this research lie in its contribution to the transition toward smart environments and sustainable smart cities. By automating waste segregation at the source and digitalizing its monitoring, the outcomes of this study have the potential to reduce manual workloads, lower the risk of pathogen exposure for sanitation workers, and increase the recovery rate of high-value recyclable materials such as metals. Furthermore, the availability of remote monitoring data delivered through the web application will provide an empirical foundation for sanitation authorities to optimize collection vehicle routes, ultimately minimizing operational costs and reducing the carbon footprint of urban waste management.

II. METHODOLOGY

This study builds upon a previous investigation that developed web- and mobile-based software to identify locations implementing the zero-waste concept [18]. The current research advances this foundation by developing an Internet of Things (IoT)-enabled smart waste bin integrated with web- and mobile-based software, named RecyClean Smart Bin. The overall research methodology employed in this study is illustrated in Figure 1 below.

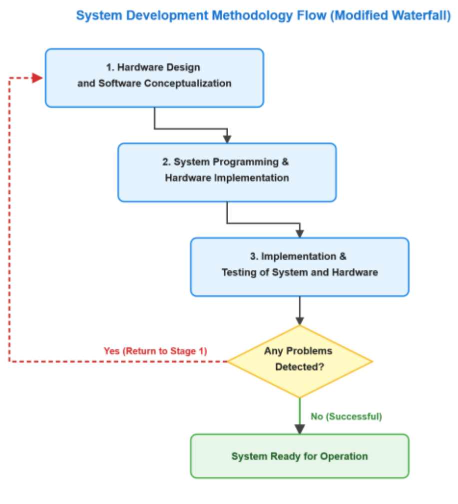

Fig. 1. Methodological Steps

The development of RecyClean Smart Bin followed a systematic sequence that began with the design of both hardware architecture and software concepts. This was followed by system programming and the fabrication of hardware components in accordance with the established design. The process then proceeded to full system implementation and functional testing of the device and integrated software. Should any issues arise during testing, the workflow returns iteratively to the design phase for refinement.

The hardware and software concept design phase began with the development of a three-dimensional model of the RecyClean Smart Bin. This was complemented by a block diagram that provided a comprehensive overview of the Internet of Things (IoT) architecture, detailing the integration of the microcontroller and associated sensor components. The system programming stage was presented in pseudocode format to ensure clarity and conciseness when describing the input, processing, and output operations of the embedded system running on the microcontroller. Hardware fabrication was subsequently executed in strict accordance with the finalized design specifications.

Following completion of the RecyClean Smart Bin prototype, the implementation phase advanced to functional testing to evaluate overall system performance. Testing was conducted and verified through live demonstrations and presentations using representative waste samples. This stage was critical in confirming that the system met field requirements and was ready for practical deployment. The primary evaluations performed on the RecyClean Smart Bin consisted of two key tests: (1) assessment of internal waste height using the ultrasonic sensor over a continuous five-day period, and (2) sorting accuracy trials involving 15 distinct waste samples, during which the readings from the proximity sensors and the correctness of waste classification were systematically verified. The functional validation was conducted in a controlled indoor environment (27°C–30°C) to maintain sensor stability. A total of 15 representative waste items (4-6 samples per category: organic, inorganic, and metallic) were used.

III. Results and Discussion

A. Results

In the software concept design phase, this study developed a web-based information system that serves as an integrated control dashboard for real-time monitoring of waste bin capacity. Architecturally, the system acquires telemetry data from the ultrasonic sensor on the IoT node via HTTP protocol transmission. The received data is subsequently processed and archived in a relational database management system (MySQL). The web interface was engineered to visualize the precise fill levels of each compartment according to material categories—namely organic, inorganic, and metallic waste. This software architecture enables effective remote monitoring, thereby eliminating the inefficiencies of manual physical inspections while providing a robust foundation for data-driven decision-making by municipal sanitation authorities.

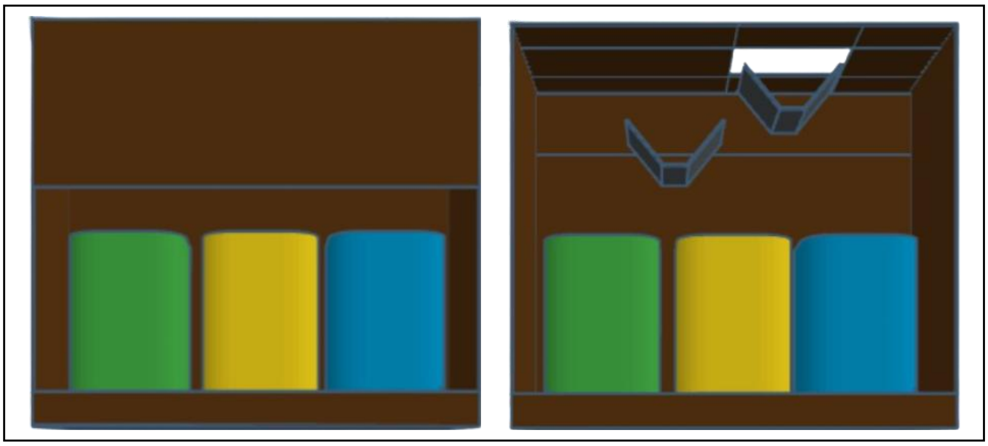

Fig. 2. Prototype Design of the RecyClean Smart Bin

Figure 2 above illustrates the prototype design of the RecyClean Smart Bin, which employs a primary structure fabricated from infraboard to accommodate the fully integrated automatic sorting mechanism. The interior of the system consists of three parallel compartments specifically allocated for the separate collection of organic (green), inorganic (yellow), and metallic (blue) waste. At the upper section of the bin, a dynamic sorting funnel mechanism is integrated, directly coupled with the sensor array and actuators. This mechanical configuration was functionally engineered to direct each waste item into the appropriate collection compartment based on real-time material identification, while simultaneously optimizing the spatial layout to provide sufficient operational space for the electronic modules and mechanical motor movements.

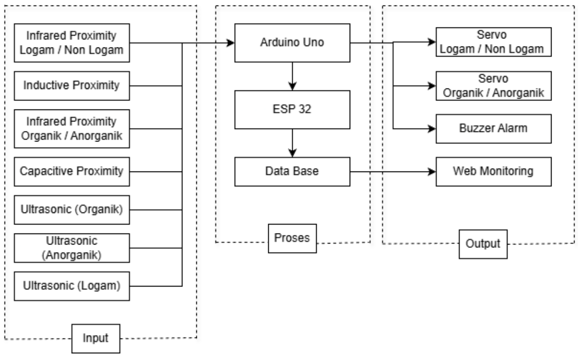

Fig. 3. Hardware Block Diagram

The operational architecture of the system is represented by a block diagram encompassing the input, processing, and output modules, as shown in Figure 3. The data acquisition module integrates multiple sensors, namely an infrared proximity sensor for object presence detection, an inductive proximity sensor for metallic material identification, a capacitive proximity sensor for organic/inorganic classification, and an ultrasonic sensor for monitoring the fill level of each compartment. All sensor readings are processed by an Arduino Uno microcontroller and transmitted via Universal Asynchronous Receiver-Transmitter (UART) serial communication to an ESP32 module, which serves as the IoT gateway. The ESP32 uploads the data to the database for real-time visualization on the web-based monitoring platform. For mechanical output, the system actuates two servo motors to execute sequential sorting—first isolating metallic waste, followed by separating organic from inorganic waste—while a buzzer actuator is triggered as an early-warning system whenever any compartment reaches its maximum capacity.

The next phase involved system programming and hardware fabrication. In this stage, the program code was structured into a two-stage identification process: first distinguishing metallic from non-metallic waste, followed by classification of organic versus inorganic waste. Figure 4 below presents the pseudocode for the first-stage material sorting mechanism. The process begins with object presence detection by the infrared proximity sensor (IR1). A stabilization delay of 300 milliseconds is then applied to prevent reading anomalies caused by physical movement of the object. Material identification is subsequently performed using an inductive proximity sensor with an oversampling technique consisting of five consecutive readings taken at 50-millisecond intervals. This oversampling method was employed to minimize signal noise and enhance detection accuracy. The final sensor value is validated through a majority-voting threshold, whereby a reading is considered valid if at least three of the five cycles register as HIGH. Based on this validated result, mechanical actuation is executed as follows: if the object is identified as metal (sensor output LOW), the servo motor directs it to the left; otherwise, non-metallic material is directed to the right. The dumping mechanism remains active for three seconds to ensure complete discharge of the object into the designated compartment. The actuator then returns to the neutral center position, ready for the next sorting cycle.

```
ALGORITHM 1: First Stage Sorting (Metal Detection)
INPUT      : irValue (Infrared Sensor Status), sensorInduktif (Inductive Sensor Pin)
OUTPUT     : servo1 actuation, System Log, Updated fill-level data
CONSTANTS  : POS_KIRI (Left Position), POS_KANAN (Right Position), POS_TENGAH (Neutral
Position)

START ALGORITHM
  // 1. Object Detection
  IF irValue == HIGH THEN
    PRINT "Objek terdeteksi oleh IR1!"

    // 2. Position Stabilization
    WAIT for 300 milliseconds

    // 3. Data Acquisition (Oversampling)
    SET induktifValue = 0
    FOR i = 0 TO 4 DO
      READ current_state FROM sensorInduktif
      induktifValue = induktifValue + current_state
      WAIT for 50 milliseconds
    END FOR

    // 4. Majority Vote Validation
    IF induktifValue >= 3 THEN
      SET induktifValue = HIGH
    ELSE
      SET induktifValue = LOW
    END IF

    // 5. Material Classification and Actuation
    IF induktifValue == LOW THEN
      PRINT "Jenis: LOGAM"
      ACTUATE servo1 TO POS_KIRI
    ELSE
      PRINT "Jenis: NON LOGAM"
      ACTUATE servo1 TO POS_KANAN
    END IF

    // 6. Object Drop and Actuator Calibration
    WAIT for 3000 milliseconds
    ACTUATE servo1 TO POS_TENGAH

    // 7. Data Synchronization
    CALL FUNCTION tampilkanKetinggian()

  END IF
END ALGORITHM
```

Fig. 4. Pseudocode for a Program to Sort Metal and Non-Metal Waste

The subsequent sorting stage involves the identification and separation of organic and inorganic waste. The pseudocode for this second-stage identification process is presented in Figure 5 below.

```
ALGORITHM 2: Second Stage Sorting (Organic and Inorganic Classification)
INPUT      : ir2Value (Infrared Sensor 2 Status), sensorKapasitif (Capacitive Sensor Pin)
OUTPUT     : servo2 actuation, System Log, Updated fill-level data
CONSTANTS  : POS_KIRI (Left Position), POS_KANAN (Right Position), POS_TENGAH (Neutral
Position)

START ALGORITHM
  // 1. Object Detection
  IF ir2Value == HIGH THEN
    PRINT "Objek terdeteksi oleh IR2!"

    // 2. Transition Delay (Mechanical Compensation)
    WAIT for 2400 milliseconds

    // 3. Data Acquisition (Oversampling)
    SET kapasitifValue = 0
    FOR i = 0 TO 4 DO
      READ current_state FROM sensorKapasitif
      kapasitifValue = kapasitifValue + current_state
      WAIT for 50 milliseconds
    END FOR

    // 4. Majority Vote Validation
    IF kapasitifValue >= 3 THEN
      SET kapasitifValue = HIGH
    ELSE
      SET kapasitifValue = LOW
    END IF

    // 5. Material Classification and Actuation
    IF kapasitifValue == HIGH THEN
      PRINT "Jenis: ORGANIK"
      ACTUATE servo2 TO POS_KANAN
    ELSE
      PRINT "Jenis: NON ORGANIK"
      ACTUATE servo2 TO POS_KIRI
    END IF

    // 6. Object Drop and Actuator Calibration
    WAIT for 3000 milliseconds
    ACTUATE servo2 TO POS_TENGAH

    // 7. Data Synchronization
    CALL FUNCTION tampilkanKetinggian()

  END IF
END ALGORITHM
```

Fig. 5. Pseudocode for an Organic and Inorganic Waste Sorting Program

The second-stage sorting is initiated when the infrared proximity sensor (IR2) detects the presence of an object. A transition delay of 2,400 milliseconds is then applied to ensure the material has fully settled in the stable sensing area. Material classification is subsequently performed by the capacitive proximity sensor using an oversampling technique, in which five consecutive readings are acquired at 50-millisecond intervals to minimize signal noise and reading anomalies. Applying the majority-voting threshold principle, the final reading is considered valid (HIGH) if at least three of the five iterations yield a positive result; in this case, the object is classified as organic waste and the servo motor is actuated to open toward the right. Conversely, if the accumulated readings fall below the threshold (LOW), the object is identified as inorganic waste and directed to the left side. The actuation position is held statically for three seconds to guarantee complete discharge of the material into the designated compartment. The actuator then automatically returns to the neutral position, preparing the system for the next sorting cycle.

Fig. 6. Results of the RecyClean Smart Bin Production Process

Figure 6 above presents the completed RecyClean Smart Bin prototype. The upper image shows the front side view, while the lower image displays the top view. The physical construction of the RecyClean Smart Bin strictly followed the hardware design established during the planning phase. Fabrication was carried out in four sequential steps as follows:

- The first step involved configuring all microcontroller components, including the ESP32 and Arduino Uno modules. After configuration, each sensor was individually tested to verify proper functionality. Any detected inconsistencies were calibrated before proceeding.
- The second step consisted of constructing the main bin frame. This process included precise measurement and cutting of infraboard panels, followed by assembly and bonding with adhesive to produce a strong and rigid structure. Infraboard (polypropylene) was selected as the primary material due to its advantageous properties: lightweight, waterproof, and highly durable (resistant to tearing or damage).
- The third step involved drilling mounting holes in the panels at the designated locations for all components.
- The final step comprised the installation of all microcontroller modules and sensors onto the completed frame, followed by comprehensive functional testing of the assembled components.

The implementation phase of the smart waste bin was executed through the operational mechanism of the RecyClean Smart Bin, which consists of two sequential sorting stages directly integrated with the web-based monitoring platform. The process is initiated when the first infrared sensor (IR1) detects an incoming object. The material is then identified by the inductive proximity sensor: metallic waste is immediately directed by the servo motor actuator to its dedicated compartment, while non-metallic materials proceed to the second sorting stage. In the subsequent stage, the object is detected once more by the second infrared sensor (IR2) and classified by the capacitive proximity sensor, separating organic and inorganic waste into their respective compartments. Complementing the overall system management, ultrasonic sensors mounted in each compartment continuously measure the volume fill level and transmit the data via the ESP32 microcontroller to the database. This enables real-time visualization of storage capacity on the website dashboard, which automatically triggers an early-warning system consisting of a local buzzer alarm and digital notifications on the web platform whenever any compartment reaches its maximum capacity. The website system provides three types of digital notifications—one each for metallic, organic, and inorganic waste. These notifications are shown in the following figures.

Fig. 7. Metal Trash Can Full Notification

Figure 7 displays the full-capacity warning for the metallic waste compartment. The dashboard indicates that the ultrasonic sensor detected a distance of 2 cm between the sensor and the waste surface. This measurement signifies that the metallic waste has reached close proximity to the sensor, thereby classifying the compartment as full. In response, the system presents a pop-up alert with the message "Warning!! Metallic Waste Bin Full," indicating that immediate handling of the compartment is required.

Fig. 8. Organic Waste Bin Full Notification

Figure 8 shows the monitoring dashboard when the organic waste compartment is declared full. The ultrasonic sensor records a distance of 2 cm to the surface of the organic waste, signifying that virtually no empty space remains. Under this condition, the system automatically triggers a red pop-up warning displaying the message "Warning!! Organic Waste Bin Full." This alert serves as a clear visual notification that the organic waste compartment requires urgent emptying.

Fig. 9. Inorganic Waste Bin Full Notification

Figure 9 illustrates the full condition of the inorganic waste compartment. As shown on the dashboard, the ultrasonic sensor detected a distance of 2 cm to the inorganic waste surface, confirming that the compartment has reached its maximum capacity. The system then displays a pop-up alert with the message "Warning!! Inorganic Waste Bin Full." These notifications demonstrate the system's capability to automatically detect near-full conditions and promptly inform users.

B. Discussion

The web-based monitoring system was tested to evaluate the accuracy of the waste fill level data acquired by the ultrasonic sensor against actual field conditions. Testing was conducted by incrementally adding waste samples belonging to three categories—organic, inorganic, and metallic—into the smart bin, followed by a direct comparison between the sensor readings and manual measurements performed over five consecutive working days. Table 1 below presents the results of the ultrasonic sensor monitoring of the distance to the waste surface.

TABLE I. TEST RESULTS FOR MONITORING THE DISTANCE OF TRASH TO AN ULTRASONIC SENSOR

Waste Categories	Time	Sensor Output (cm)	Actual Distance (cm)	Error
Organic	2025-12-05 08:59:58	10.4	9.8	0.6
Inorganic		10.2	9.7	0.5
Metal		29.7	30.2	0.5
Organic	2025-12-08 09:00:34	10.5	11.1	0.6
Inorganic		20.1	18.7	0.4
Metal		29.1	29.3	0.2
Organic	2025-12-09 08:58:21	11.6	11.4	0.2
Inorganic		25.3	24.9	0.4
Metal		29.1	29.3	0.2
Organic	2025-12-10 08:59:43	10.2	11.8	0.4
Inorganic		15.3	14.9	0.4
Metal		27.2	27.5	0.3
Organic	2025-12-11 08:58:54	10.8	11.2	0.4
Inorganic		14.9	15.2	0.3
Metal		28.1	28.2	0.1

The monitoring test results showed a minimal discrepancy between the ultrasonic sensor readings of waste distance and the actual field measurements, with a maximum deviation of only 0.6 cm. This confirms that the ultrasonic sensor performed reliably, owing primarily to the calibration performed prior to testing. Subsequent performance evaluation of the system was conducted using 15 representative waste samples drawn from the metallic, inorganic, and organic categories. Overall, the automated sorting mechanism achieved a satisfactory success rate, correctly identifying and classifying 12 out of the 15 items. In particular, testing of metallic materials demonstrated that the sensor system operated with high precision and optimal performance; all tested samples—including beverage cans, scissors, iron fragments, and staple pieces—were successfully detected and accurately classified into the designated bin.

This performance consistency was also evident in the testing of inorganic materials, where the system successfully recognized items such as paper cups, plastic bottles and cups, as well as dry paper and tissues with high accuracy. Nevertheless, a classification anomaly occurred during testing of the dry leaf sample, which was misclassified as inorganic material. This failure is strongly attributed to the reduced density and extremely low moisture content of the dry leaves, which triggered a dielectric response in the capacitive sensor that closely resembled the physical characteristics of inorganic waste.

Validation of the organic waste category, using samples of fresh leaves, cucumber, and tomato, confirmed that the system performed accurate and targeted sorting. However, the instrument's sensitivity limitations became apparent when tested with wet paper and wet tissue samples, which were erroneously classified as organic material. This shift in sensor response is technically attributed to the high moisture retention within the pores of the paper and tissue. The elevated water content significantly distorted the capacitive sensor readings, causing the system to interpret the samples as liquid-rich biological structures. The complete performance evaluation results are presented in Table 2 below.

TABLE II. PERFORMANCE EVALUATION OF THE RECYCLEAN SMART BIN SYSTEM

Sample Materials	Sensor Detection			Results
	Metal	*Organic*	*Inorganic*	
Can	✓	-	-	correct
Scissors	✓	-	-	correct
Metal Scraps	✓	-	-	correct
Staple Remnants	✓	-	-	correct
Paper Cups	-	-	✓	correct
Plastic Cups	-	-	✓	correct
Paper	-	-	✓	correct
Tissue Paper	-	-	✓	correct
Plastic Bottles	-	-	✓	correct
Dried Leaves	-	-	✓	incorrect
Leaves	-	✓	-	correct
Cucumbers	-	✓	-	correct
Tomatoes	-	✓	-	correct
Wet Paper	-	✓	-	incorrect
Wet Wipes	-	✓	-	incorrect

Compared to the system developed by [13], which achieved a sorting accuracy of 75% for two categories, our proposed RecyClean bin achieved a higher accuracy of 80% across three categories. Additionally, our ultrasonic sensor's maximum deviation of 0.6 cm outperforms the average error reported in [12], which ranged between 1.0–1.5 cm. This precision is attributed to the implemented stabilization delay and majority-voting algorithm.

The selection of a capacitive sensor was based on its ability to detect changes in the dielectric constant. However, the misclassification of wet paper as organic waste occurs because water has a high dielectric constant (~80). When paper absorbs moisture, its dielectric properties shift to mimic biological/organic materials. Similarly, dried leaves were misclassified as inorganic due to the loss of moisture, reducing their dielectric response below the organic threshold. Future calibration will involve multi-threshold logic to account for moisture-dependent variables.

IV. CONCLUSION

Based on the experimental results, this study has successfully addressed key technical challenges in modern waste management by developing an integrated Internet of Things (IoT) solution that tackles three interrelated issues: automatic waste classification, real-time capacity monitoring, and remote data accessibility. The RecyClean Smart Bin prototype effectively classifies metallic, organic, and inorganic waste with satisfactory accuracy. Evaluation results confirm that the integrated proximity sensor reliably detects metallic materials, while the web-based application enables accurate remote monitoring of bin fill levels. Overall, the study has achieved its primary objective of designing and implementing a functional smart waste-sorting prototype.

Reliability validation of the multi-sensor integration demonstrated that 12 out of 15 representative waste samples were correctly identified and sorted. The web-based information system further exhibited high precision, with a maximum deviation of only 0.6 cm between ultrasonic sensor readings and actual waste levels, thereby providing users with dependable real-time capacity information.

Future development will focus on enhancing both software and hardware aspects. On the software side, additional features such as integration with waste collection truck routing systems are planned. On the hardware side, the implementation of protective covers or enclosures for the proximity sensor is recommended to minimize the influence of moisture and wet waste conditions on sensor performance. These improvements are expected to further strengthen the system's robustness and practical applicability in real-world campus and urban environments. Future work will expand the experimental validation by increasing the sample size to 100+ items with higher diversity in moisture levels and shapes. Subsequent studies will also implement comprehensive statistical performance metrics, including a confusion matrix to calculate precision, recall, and F1-score for each waste category, providing a more rigorous evaluation of the system's reliability in real-world campus environments.

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