



Modeling Automatic Waste Sorting Using Ultrasonic Sensors

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Abstract

Waste management remains a critical challenge due to the increasing volume of solid waste and the inefficiency of manual sorting processes. This study develops and implements an Internet of Things (IoT)-based automatic waste sorting system using an ESP32 microcontroller. The proposed system integrates ultrasonic sensors, an inductive proximity sensor, and an MQ135 gas sensor to automatically detect and classify metal and non-metal waste. The system also connects to the Blynk platform to enable real-time monitoring and notification capabilities, allowing users to observe system conditions remotely. Experimental evaluation is conducted using 100 waste samples consisting of 50 metal objects and 50 non-metal objects. The results show that the system correctly classifies 48 metal samples and 42 non-metal samples. Meanwhile, 8 non-metal samples are misclassified as metal, and 2 metal samples are incorrectly detected. Based on these results, the system achieves an overall classification accuracy of 90%, indicating reliable performance in distinguishing between metal and non-metal waste materials. Further evaluation using precision, recall, and F1-score metrics confirms the effectiveness of the proposed system. The metal class achieves a precision of 85.71%, a recall of 96%, and an F1-score of 90.57%. For the non-metal class, the system records a precision of 95.45%, a recall of 84%, and an F1-score of 89.39%. These results demonstrate balanced classification performance for both categories. Therefore, the developed IoT-based automatic waste sorting system provides a practical and reliable approach for improving waste management efficiency and supporting intelligent waste processing based on material characteristics.

Keywords:

Waste sorting, Internet of Things, Microcontroller, Ultrasonic Sensors

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1. Introduction

Waste Rapid urbanization and population growth significantly increase the volume of municipal solid waste in many cities. Traditional waste management systems rely heavily on manual sorting and collection processes, which often lead to inefficiency, environmental pollution, and increased operational costs. Manual waste separation also exposes workers to health risks due to direct contact with hazardous materials. Researchers therefore emphasize the need for intelligent and automated waste management systems that can improve sorting efficiency and reduce human intervention. Smart waste bins and automated sorting technologies have emerged as promising solutions that integrate sensors, microcontrollers, and monitoring systems to optimize waste handling processes and support sustainable urban environments. These developments highlight the importance of integrating sensing technologies to monitor waste conditions and automate sorting operations in real time [1], [5], [9].

In recent years, the development of smart waste bins has received considerable attention in the context of smart cities and Internet of Things (IoT) technologies. Smart

bins utilize sensors and embedded systems to monitor waste levels, detect waste types, and optimize collection schedules. Several studies demonstrate that integrating sensors with microcontroller platforms enables real-time monitoring of waste conditions and improves the efficiency of waste collection processes. Ultrasonic sensors in particular provide an effective solution for measuring object distance and detecting the presence of waste inside containers. Their low cost, reliability, and ease of integration make them suitable for smart waste management applications. However, many existing implementations focus primarily on monitoring waste levels rather than performing automatic sorting or classification of waste materials [2], [3], [10].

Ultrasonic sensing technology plays a crucial role in automation systems because it enables non-contact measurement and object detection. In waste management applications, ultrasonic sensors detect the distance between the sensor and the waste surface, allowing the system to determine the presence or quantity of waste in a container. Several studies demonstrate the successful integration of ultrasonic sensors with microcontroller platforms such as Arduino for developing intelligent waste monitoring systems. These systems improve operational efficiency by automatically detecting waste levels and triggering alerts when containers reach certain thresholds. Despite these advancements, most implementations still concentrate on waste monitoring rather than modeling automated sorting mechanisms that classify waste types before disposal [7], [12], [19].

Researchers also investigate the integration of IoT technologies to enhance the performance of smart waste systems. IoT-based solutions allow sensors to transmit real-time data to centralized platforms for monitoring, analysis, and decision-making. Such systems support efficient waste collection routes, reduce operational costs, and improve the responsiveness of municipal waste services. In addition, IoT-based architectures enable scalability and integration with broader smart city infrastructures. However, the majority of IoT-based waste management systems primarily address monitoring and collection optimization, while the issue of automated waste sorting at the source remains relatively underexplored. This limitation indicates the need for further research that focuses on sensor-driven sorting mechanisms capable of improving waste separation accuracy and efficiency [4], [8], [11].

Automatic waste sorting technologies have also been explored using various sensing and intelligent approaches. Some systems combine image processing, artificial intelligence, and machine learning to classify different waste materials such as plastic, paper, and metal. These approaches demonstrate promising performance but often require high computational resources, specialized hardware, and complex system architectures. In contrast, sensor-based approaches offer a simpler and more cost-effective alternative for practical implementation in household or community waste bins. Ultrasonic sensors can be integrated with mechanical actuators or sorting mechanisms to detect waste characteristics and direct items into appropriate containers. Nevertheless, many existing prototypes remain limited in scalability and modeling accuracy [13], [14], [16].

In addition to sensor-based detection, recent studies explore advanced automation techniques for improving waste sorting efficiency. Robotic systems and artificial intelligence algorithms have been used to identify and separate recyclable materials in industrial waste management facilities. These technologies provide high accuracy in waste classification and support large-scale recycling operations. However, such systems often involve expensive hardware components and sophisticated algorithms that limit their accessibility for small-scale or household waste management applications. Consequently, simpler sensor-based approaches, particularly those

utilizing ultrasonic sensing technology, remain attractive for developing practical and affordable automated sorting solutions [15], [17], [18].

Another important issue in smart waste management research concerns system reliability and accuracy in detecting waste presence and characteristics. Ultrasonic sensors must operate under various environmental conditions, including irregular waste shapes, different material surfaces, and varying distances between the sensor and objects. Researchers therefore analyze sensor accuracy, filtering techniques, and calibration methods to improve measurement reliability. Proper modeling of ultrasonic sensor behavior becomes essential for ensuring that automated sorting systems operate accurately and consistently. Without robust modeling and calibration, sensor readings may produce errors that affect the performance of the sorting mechanism [8], [20].

Based on these challenges, the development of an automated waste sorting model using ultrasonic sensors becomes an important research direction. Modeling enables researchers to analyze sensor behavior, system architecture, and sorting mechanisms before implementing the physical prototype. By integrating ultrasonic sensing with automated control systems, waste sorting processes can be performed more efficiently and consistently. Such an approach supports the broader goals of smart waste management by reducing manual intervention, improving waste separation accuracy, and enhancing environmental sustainability. Therefore, this study focuses on modeling an automatic waste sorting system using ultrasonic sensors to provide a practical framework for implementing efficient and intelligent waste management solutions [1], [5], [10].

2. Related Works

Researchers have explored various smart waste management systems to improve waste monitoring and collection efficiency. Yusof et al. developed a smart waste bin equipped with sensors and real-time monitoring capability to track waste levels inside containers. Their study demonstrated that integrating sensors with embedded systems significantly improved waste collection efficiency and reduced overflow conditions in urban areas. The system provided reliable real-time data for monitoring waste conditions. However, the study primarily focused on monitoring waste levels rather than implementing automatic sorting mechanisms. As a result, the system did not address the challenge of separating different waste types automatically at the source [1].

Shaharil and Po'ad designed an Arduino-based smart dustbin using ultrasonic sensors to detect waste levels and automate lid operation. Their system successfully demonstrated that ultrasonic sensors could accurately detect the presence of waste and trigger automated responses in the system. The implementation proved cost-effective and suitable for small-scale smart waste applications. Despite these advantages, the proposed design mainly addressed bin automation and waste level detection. The system did not incorporate mechanisms for classifying or sorting waste materials, which remains a critical requirement in modern waste management systems [2].

Istiana implemented ultrasonic sensors in smart trash box systems to improve waste detection and monitoring. The study showed that ultrasonic sensors effectively measured the distance between the sensor and waste surfaces, enabling the system to determine container capacity accurately. The design successfully integrated microcontrollers and sensors to automate monitoring processes. However, the system remained limited to waste detection functionality. It did not include automated sorting logic or mechanisms that could direct waste into separate compartments based on specific characteristics [3].

Dari et al. proposed an IoT-based smart trash bin monitoring system that transmitted sensor data to a centralized platform for real-time analysis. Their study demonstrated that IoT connectivity enhanced the ability to monitor waste levels remotely and improved the efficiency of waste collection scheduling. The integration of communication technologies allowed the system to support smart city waste management infrastructures. Nevertheless, the study mainly focused on monitoring and data transmission. It did not investigate modeling or automation techniques for waste sorting using sensor-based detection systems [4].

Qureshi et al. investigated smart bin waste monitoring systems for sustainable biomedical waste management. Their research emphasized the importance of intelligent waste management solutions in reducing environmental risks associated with improper waste handling. The study utilized sensor-based monitoring combined with data analysis to improve waste tracking and disposal processes. The findings showed that sensor-based systems could significantly improve waste management efficiency. However, the research concentrated on monitoring biomedical waste and did not specifically address automated waste sorting mechanisms using ultrasonic sensor modeling [5].

Pratama and Harijono analyzed the performance of ultrasonic sensors in smart trash bin technology using Arduino-based microcontrollers. Their study evaluated the accuracy and reliability of ultrasonic sensors in detecting waste levels within containers. The results showed that ultrasonic sensors provided stable and accurate measurements when properly calibrated. The research highlighted the importance of sensor reliability in smart waste systems. However, the work mainly focused on sensor performance analysis rather than developing a complete automated sorting model that could classify waste items in real time [7].

Wijaya et al. conducted a comparative analysis of ultrasonic sensor accuracy for smart trash applications. Their study evaluated the measurement precision of ultrasonic sensors under different conditions and demonstrated that filtering techniques improved sensor accuracy and reliability. The research contributed valuable insights into improving sensor-based detection systems in waste management applications. Nevertheless, the study mainly addressed measurement accuracy and sensor performance. It did not extend the work toward modeling automated waste sorting systems that utilize ultrasonic sensing to control mechanical separation processes [8].

Several researchers also explored automated waste segregation systems using various technologies. Raut et al. developed a waste segregation prototype designed to separate waste materials using mechanical and electronic components. The system demonstrated the feasibility of automating waste separation processes and reducing manual sorting efforts. Similarly, Nafiz et al. proposed a deep learning-based waste segregation system that used image recognition techniques to classify waste materials automatically. Although these approaches showed promising results, they often required complex hardware and computational resources. In contrast, sensor-based approaches using ultrasonic sensors provided simpler and more cost-effective solutions for practical implementation. These limitations highlighted the need for further research on modeling efficient automatic waste sorting systems that rely on simple yet reliable sensing technologies [13], [16].

3. Proposed Method

This study applies the Research and Development (RnD) approach combined with experimental validation to design and evaluate an automatic waste sorting system based on ultrasonic sensing and IoT technology. The development process consists of six main stages: literature study, system design, prototype development, testing,

evaluation, and conclusion. During the literature study stage, we analyze prior work related to sensor-based waste management systems and IoT integration. The knowledge obtained from this stage guides the design of an automatic waste sorting system that integrates an ESP32 microcontroller, ultrasonic sensor, inductive proximity sensor, MQ135 gas sensor, and the Blynk IoT platform. The system aims to automatically classify waste objects into metal and non-metal categories while simultaneously monitoring environmental gas conditions.

In the system design stage, we construct a block diagram and define the operational workflow of the device. The ultrasonic sensor functions as the primary detector to identify the presence of an object inside the input chamber. The distance between the sensor and the detected object is calculated using the ultrasonic time-of-flight principle. Let t represent the time interval between the transmitted and received ultrasonic pulse, and v denote the speed of sound in air approximately 343 m/s . The distance d between the sensor and the object is computed as

$$d = \frac{v \times t}{2}$$

If the measured distance d is less than a predefined threshold d_{th} , the system assumes that a waste object is present. After detection, the inductive proximity sensor determines whether the object contains metal. The sensor output can be expressed as a binary classification function

$$M(x) = \begin{cases} 1, & \text{if metal is detected} \\ 0, & \text{otherwise} \end{cases}$$

where x represents the detected waste object. When $M(x) = 1$, the control system directs the servo motor to rotate toward the metal container. Otherwise, the servo directs the object toward the non-metal container.

The ESP32 microcontroller processes all sensor inputs and controls the sorting mechanism. The rotation angle of the servo motor determines the destination of the waste object. Let θ represent the servo angle, defined as

$$\theta = \begin{cases} \theta_m, & \text{if } M(x) = 1 \\ \theta_n, & \text{if } M(x) = 0 \end{cases}$$

where θ_m represents the servo position for the metal bin and θ_n represents the position for the non-metal bin. After the sorting process, the MQ135 gas sensor monitors the surrounding air quality to detect potentially harmful gases emitted by waste materials. The gas concentration G is measured from the analog sensor output and compared with a predefined threshold G_{th} . If $G > G_{th}$, the system automatically sends a warning notification through the Blynk IoT platform. The notification decision function can be expressed as

$$N(G) = \begin{cases} 1, & \text{if } G > G_{th} \\ 0, & \text{if } G \leq G_{th} \end{cases}$$

where $N(G) = 1$ triggers a notification to the monitoring application.

The prototype development stage includes assembling the hardware components, programming the ESP32 using the Arduino IDE, and integrating the system with the Blynk platform for remote monitoring. After the prototype is completed, experimental testing is conducted to evaluate the performance of each sensor and the overall system.

The evaluation phase measures several performance indicators, including sorting accuracy, sensor response time, and system reliability. The results of these experiments provide insight into the effectiveness of the proposed automatic waste sorting model and support further improvements in the design of sensor-based waste management systems. Fig. 1 presents the system block diagram, which illustrates the relationship between the input sensors and output components.

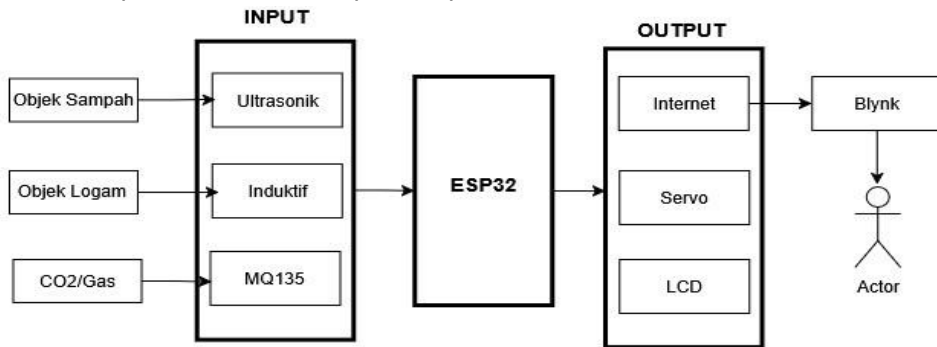


Fig.1 Block Diagram

The overall system workflow is depicted in Fig.1 The system starts with hardware initialization and Wi-Fi connection. Once connected to the network, the device waits for input from the user. When the trash object is detected by the ultrasonic sensor, the system reads the data from the inductive proximity sensor to determine if the object is metal. If the object is metal, the servo is directed to the metal bin. If not, it is directed to the non-metal bin. Next, the MQ135 gas sensor will activate to detect the possible presence of hazardous gas. If gas is detected, the system will send a notification to the Blynk app automatically. Once the process is complete, the system returns to standby mode and is ready to receive the next input.

4. Experimental Setup

Testing is carried out to evaluate the performance of the IoT-based automatic metal and non-metal waste sorting device that has been designed and made. The main components in this tool include the ESP32 microcontroller, inductive proximity sensor, HC-SR04 ultrasonic sensor, MQ135 gas sensor, MG996R servo motor, and I2C LCD module. In addition, the Blynk application is used as an IoT-based monitoring media via a Wi-Fi connection.

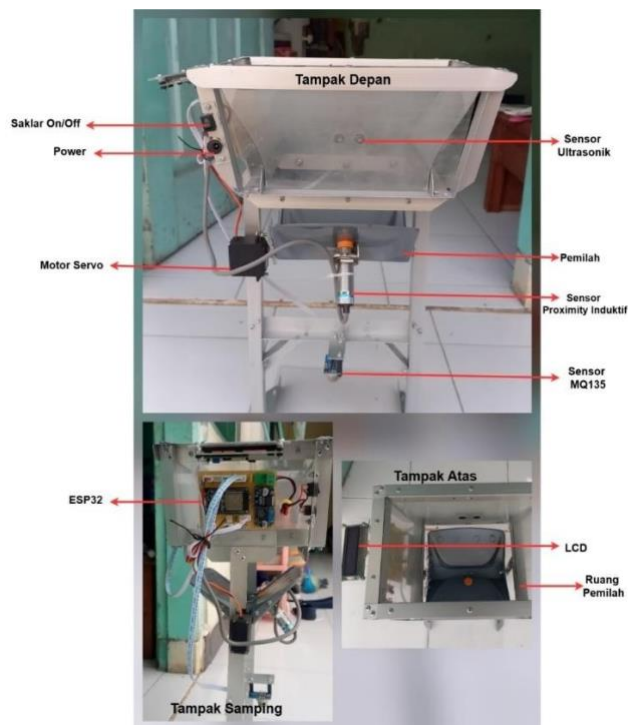


Fig. 2 Tool Implementation

In Fig. 2, the components are assembled on an aluminum-based frame. An ultrasonic sensor is mounted at the top to detect incoming objects. A proximity sensor is placed at the bottom of the input line to read the type of material. The MQ135 gas sensor is placed on the non-metallic bin to detect harmful gases. A servo motor is mounted on the drive mechanism of the waste sorting flap. The entire system is controlled and monitored in real-time through an ESP32 connected to a Wi-Fi network.

The data collection procedure is carried out by inserting various types of waste into the device. Data is recorded based on the proximity sensor detection results (metal or non-metal), servo movement decisions, LCD display, CO₂/gas presence detection, and notifications from the Blynk application. The waste used includes 20 samples, 10 non-metallic and 10 metallic samples. Testing was carried out 5 times on each sample, the recapitulation of test data is presented in table 4.1 below.

Table 1: Testing of Non-metals object

Name	Type	Detected	Not Detected	Trial Total
Plastic	Non-metals	5	0	5
Paper	Non-metals	4	1	5
Tissue	Non-metals	4	1	5
Wallet	Non-metals	1	4	5
Platic Bottle	Non-metals	5	0	5
Masks	Non-metals	5	0	5
Soap wrapper	Non-metals	4	1	5
Cassing hp	Non-metals	5	0	5
Charger hp	Non-metals	4	1	5

Table 2: Testing of metals object

Name	Type	Detected	Not Detected	Trial Total
Glasses	Non-metals	5	0	5
Cans	Metals	5	0	5
Watches	Metals	5	0	5
Lamp	Metals	5	0	5
Spoon	Metals	5	0	5
Coin money	Metals	5	0	5
Scissors	Metals	3	2	5
Tweezers	Metals	5	0	5
Motor key	Metals	5	0	5
Flashlight	Metals	5	0	5
Metal Cup	Metals	5	0	5
TOTAL		90	10	100

Tables 1 and 2 present the experimental results of the waste detection system for non-metal and metal objects. Table 1 shows the testing results for nine types of non-metal objects, including plastic, paper, tissue, wallet, plastic bottle, masks, soap wrapper, phone casing, and phone charger. Each object was tested five times, resulting in a total of 45 trials. Most non-metal objects were detected successfully, such as plastic bottles, masks, and phone casings, which achieved perfect detection rates. However, several objects such as paper, tissue, soap wrappers, and phone chargers experienced one missed detection in each set of trials. The wallet object showed the lowest detection performance, with only one successful detection out of five trials.

Table 2 presents the testing results for metal objects, which include cans, watches, lamps, spoons, coins, scissors, tweezers, motor keys, flashlights, and metal cups. Each object was also tested five times. Most metal objects were detected perfectly, achieving five successful detections in all trials. Only the scissors object produced two missed detections, which slightly reduced the detection rate for this category. Overall, the combined results from both tables show 90 successful detections and 10 missed detections out of 100 trials, indicating that the system achieves a detection accuracy of 90%. These results demonstrate that the proposed automatic waste sorting system performs reliably in identifying both metal and non-metal objects, although certain object shapes and materials may slightly affect detection performance.

5. Result and Analysis

System testing was conducted to evaluate the detection accuracy between metal and non-metal waste. The experiment used 100 test trials consisting of 50 metal samples and 50 non-metal samples. Each object was placed in the detection area to trigger the sorting process. The ultrasonic sensor first detected the presence of the object. The inductive proximity sensor then determined whether the object contained metal. Based on this detection, the system directed the waste to the appropriate bin using the servo motor mechanism. All classification results were recorded during the testing process. The final results were analyzed to measure the number of correct and incorrect classifications. Fig. 3 presents the confusion matrix, which illustrates the performance of the system in distinguishing metal and non-metal waste.

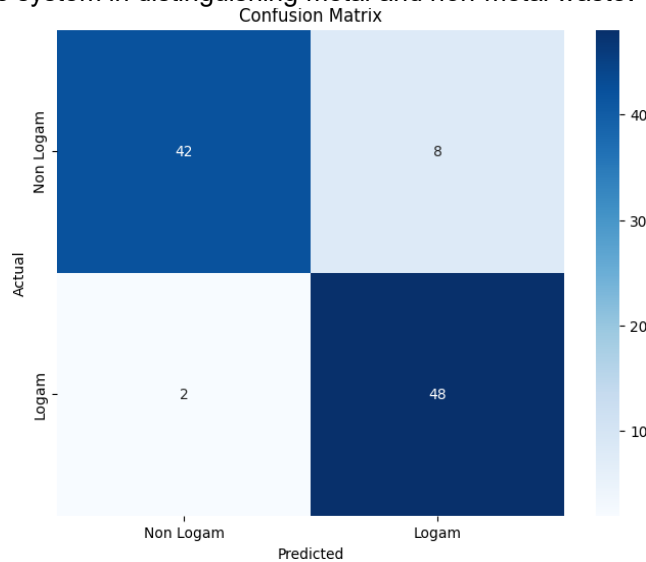


Fig 3 Confusion matrix

From the experimental testing, we obtain classification results for 100 waste samples consisting of metal and non-metal objects. The results show that the system correctly identifies 42 out of 50 non-metal samples as non-metal (True Positive), while 8 samples are incorrectly classified as metal (False Negative). For the metal class, the system successfully detects 48 out of 50 samples correctly (True Negative), while only 2 samples are misclassified (False Positive). Based on these results, the overall system accuracy is calculated using the standard accuracy formulation $(TP + TN)/(TP + TN + FP + FN)$. The calculation produces an overall accuracy value of 90%, indicating that the developed automatic waste sorting system can achieve reliable classification performance in distinguishing metal and non-metal materials.

Further evaluation is conducted using precision, recall, and F1-score metrics to measure classification performance in more detail. For the metal class, the system achieves a precision value of 85.71%, which indicates that most predicted metal objects are correctly classified. The recall value reaches 96%, meaning that the system successfully detects almost all actual metal samples in the dataset. These values produce an F1-score of 90.57%, demonstrating strong classification capability in identifying metallic waste objects. The high recall value also indicates that the sensor-

based detection mechanism performs effectively in recognizing metal materials during the sorting process.

For the non-metal class, the system records a precision value of 95.45% and a recall value of 84%, resulting in an F1-score of 89.39%. These results indicate that the system can achieve balanced performance in detecting both waste categories. Overall, this study can achieve an effective automatic sorting mechanism with high reliability for practical waste management applications. The overall accuracy of 90% demonstrates that the proposed IoT-based waste sorting system is capable of classifying metal and non-metal waste efficiently and can support the development of intelligent waste processing systems based on material characteristics.

6. Conclusion

This study successfully develops and implements an Internet of Things (IoT)-based automatic waste sorting system using an ESP32 microcontroller. The proposed system integrates ultrasonic sensors, inductive proximity sensors, and an MQ135 gas sensor to detect and classify metal and non-metal waste automatically. In addition, the system connects to the Blynk platform to provide real-time monitoring and notification capabilities. The experimental results demonstrate that the developed system operates effectively in detecting waste objects and directing them to the appropriate container based on their material characteristics.

From the experimental evaluation, we obtain classification results based on 100 waste samples consisting of metal and non-metal objects. The system correctly identifies 42 out of 50 non-metal samples, while 8 samples are incorrectly recognized as metal. For the metal class, the system successfully detects 48 out of 50 samples correctly, while only 2 samples are misclassified. Based on these results, the overall classification accuracy calculated using the standard accuracy formula reaches 90%. These findings indicate that the proposed automatic waste sorting system can achieve reliable performance in distinguishing metal and non-metal waste materials.

Further performance evaluation using precision, recall, and F1-score metrics confirms the effectiveness of the system. For the metal class, the system achieves a precision value of 85.71%, a recall value of 96%, and an F1-score of 90.57%. Meanwhile, for the non-metal class, the system records a precision of 95.45%, a recall of 84%, and an F1-score of 89.39%. These results demonstrate that the proposed system can achieve balanced classification performance for both waste categories. Therefore, we obtain strong evidence that the developed IoT-based automatic waste sorting system provides a reliable and practical solution for improving waste management efficiency and supporting intelligent waste processing based on material characteristics.

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