**IoT-Enabled Smart Bins: Deep Learning for Waste Segregation**

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**Abstract.** This study tackles Malaysia’s expanding solid waste management problem, which is made worse by the country’s fast urbanization and outdated, ineffective systems. Current methods, which are mainly based on manual segregation and land filling, are unable to manage the growing volume and diversity of trash, resulting in inefficient recycling, hazards to public health, and environmental deterioration. The proposed solution involves an Internet of Things-powered intelligent that support handling system that leverages artificial intelligence to autonomously categorize and detect garbage accumulation. A Raspberry Pi, HC- SR04 sensors for level monitoring, a Pi Camera for taking pictures, and a servo motor for automated sorting are all included in a prototype that uses a dual-bin configuration for general and recyclable waste. Waste is divided into five categories by a MobileNet-SSDv2 deep learning model that was trained on a waste photos dataset: paper, glass, cans, plastic, and general trash. For real-time monitoring and analysis, data is shown on Grafana and stored locally using InfluxDB. While real-world scenarios demonstrated enhanced accuracy of 84.46%, controlled testing of the deep learning model produced a mean Average Precision (mAP) of 71.25%. While "glass" displayed the lowest accuracy (77.3%), the "can" category had the highest accuracy (90%). Ultrasonic sensors showed excellent accuracy in detecting waste levels. The system’s benefits include increased rates of recycling and segregation, improved efficiency through information-driven choices and continuous monitoring, improved public health because overflowing bins are prevented, less environmental impact from landfill usage, and data-driven optimization for resource allocation and urban planning. This study shows how IoT and AI have the potential to transform waste management practices to support a more sustainable future.

# **INTRODUCTION**

Economic growth and urban development have contributed to higher consumption that eventually increases solid waste output. Current methods of solid waste management, such as landfilling and manual segregation, could not cope with the increase in the volume and variety of waste outputs. Thus, this scenario is exacerbated by rapid industrial development, which inhibits public healthcare and environmental safety [1]. Lack of waste segregation at the source and overdependence on landfills contribute to the waste of opportunities to recover recyclable materials. These activities limit recycling initiatives and further encourage greenhouse gas emissions.

Effective waste management brings many benefits to Malaysian society in terms of economics and environmental conservation. The act of proper segregation at the waste collection source point emphasizes the recovery of recyclable materials [2]. This recyclable material has an economic benefit to reduce depletion of raw material and discovery of alternative uses of waste products in the same ecosystems that produced them. Furthermore, reduction of solid waste reduces pollution and enhances awareness of public and industrial hazardous waste.

The existing small-scale recycling efforts of solid waste material can be accelerated by the integration of Internet of Things (IoT) technology. Normally, recycling is essentially carried out at industrial waste collection sites [3]. However, the government’s effort to introduce waste segregation is thwarted by minimal participation from the public due to a lack of awareness and incentives. The introduction of IoT real-time smart waste bins equipped with sensors monitoring facilities can enable them to check waste fill levels and may optimize waste collection schedules and route management. Recent development of IoT integration with convolutional neural networks (CNNs) enables automatic waste type identification and sorting efforts. These efforts can enhance recycling rates and minimize improper disposal of solid waste that can impact the environment [4].

Research has shown that most garbage management systems fail to give enough consideration to how inefficiently they sort and collect trash, which causes bins to overflow, poses health risks, and leads to more trash going to landfills [5].

The first section of the paper begins with a comprehensive review of existing literature, which establishes the theoretical foundation for the study and emphasizes the important role that the Internet of Things (IoT) and data analytics play in the field of waste management. The second section details the methodology, which shows the experimental design and data collection procedures, including the deployment of IoT devices and analytical tools. The subsequent sections present the findings and analyses from the case study, followed by a discussion on the implications and practical applications of IoT and analytics in optimizing waste management practices. The report concludes with a concise summary of the research outcomes, highlighting the transformative potential of data-driven approaches in enhancing resource efficiency and environmental sustainability in urban areas.

# **LITERATURE REVIEW**

Various research has proven that the integration of Internet of Things (IoT) technology provides solutions to waste management challenges by facilitating real-time monitoring of waste levels and enabling optimized collection routes and schedules [6]. The consensus on the benefits of integrating Internet of Things (IoT) technology into waste man- agreement systems typically involve smart bins equipped with various sensors (ultrasonic, gas, cameras, and GPS) to monitor fill levels, waste composition, and location [7]. Many systems are designed to enable the IoT systems’ data to be transmitted via communication networks (Wi-Fi, LoRaWAN, cellular) to a central management system for analysis and routing [8]. Recent researchers embarked on the incorporation of AI and machine learning for auto- mated waste classification and predictive modelling, improving efficiency and reducing costs [9]. The key benefits of the AI-based IoT for waste management include real-time monitoring preventing overflowing bins and associated health hazards, optimized collection routes, reduced fuel consumption and emissions, and increased recycling rates minimizing landfill usage.

Systematic reviews showed that an IoT system using a dual-sensing approach (ultrasonic and methane sensors) achieved 95% accuracy in fill-level detection and 92% accuracy in detecting spoilage. It is reported that there was a 20% reduction in overflowing bins and a 15% reduction in collection frequency through real-time data driven [10]. Researchers view these improvements as significant cost savings in fuel, labour, and vehicle maintenance while simultaneously reducing the environmental impact of waste disposal. The use of AI for automated waste classification further enhances efficiency and accuracy in sorting recyclables [11]. However, the integration of IoT and AI in waste management is not without challenges. These challenges are such as initial infrastructure costs, the need for technical expertise, data privacy and security concerns, and the potential for inconsistent sensors [12]. Rapid urbanization, new township expansion, and high public healthcare demand outweigh the above cost of infrastructure and technical expertise requirements. Therefore, making IoT-based smart waste management a promising solution for addressing the growing problem of waste disposal in urban areas [13]. Further research on the integration of IoT in urban and industrial waste management is needed to facilitate end-to-end eco-friendly waste recycling and disposal to fully realize the potential of this technology.

# **PROPOSED SOLUTION**

Repeatedly, researchers pointed out that inefficiencies in garbage segregation and collection are the major cause of many cities’ current waste management systems’ failure. Existing labour-intensive waste collection is more focused on disposal of solid waste than on providing real-time monitoring capabilities [14]. Furthermore, waste products are economically feasible to generate income if they are managed automatically using AI-based IoT systems [15]. Thus, a smart waste management system is proposed in this research to address these serious inadequacies. Utilizing artificial intelligence (AI) and the Internet of Things (IoT), this system improves sustainability and efficiency by automating garbage sorting and level detection [16]. In this work, the system will use a dual-bin setup (general waste and recyclables) with a servo motor and sensors for automated sorting. With the integration of a camera and sensors, a Raspberry Pi microcontroller will function as the central processing unit, tracking waste levels and categorizing different forms of garbage. Grafana will allow for real-time monitoring and data visualization when Influx-DB is used to gather and store the data locally. This method offers real-time data, automatic sorting, and a platform for data-driven decision-making, thereby directly addressing the observed inefficiencies in conventional systems. The proposed work of the integration of IoT sensor technology into local waste segregation systems offers a comprehensive and sustainable solution to the challenges of modern waste management. The combination of real-time monitoring, automated sorting, and data-driven decision-making leads to significant cost savings, environmental benefits, and improvements in public health and hygiene. The feasibility and effectiveness of this approach are supported by numerous research studies.

# **PROPOSED SYSTEM DESIGN**

Figure 1 shows the overall system diagram that consists of an HC-SR04 sensor and a Pi camera that are attached to the Raspberry Pi 4 Model B to produce the prototype of the smart waste management system. InfluxDB is used to store the data gathered locally from the sensors. The servo motor will be used as an actuator that provides output or an action upon receiving data from inputs. In this case, it is object detection. The data from InfluxDB will be displayed at Grafana to produce data visualization to allow display from the administrator. The diagram indicates that two HC-SR04 ultrasonic sensors and a servo motor are connected to a Raspberry Pi 4 Model B. Resistors of 100 ohms, and 200 ohms are placed for the HC-SR04 ultrasonic sensors. These resistors are used to form a voltage divider to reduce the 5V output of the sensors to a safe value for the Pi’s GPIO, which operates at 3.3V. This is to prevent the GPIO pins from being spoilt by high voltage. Additionally, a 100-ohm resistor is added to the servo motor to reduce its turning force, preventing the servo from becoming too powerful and potentially damaging itself. Figure 2(a) shows the front of the prototype, while Figure 2(b) shows the back of the prototype.

**A computer chip with many blue objects

AI-generated content may be incorrect.**

**FIGURE 1**.Overall system design



**(a)** **(b)**

**FIGURE 2.** The prototype design: (a) front and (b)

A MobileNet-SSDv2 deep learning model was trained to classify waste images into five categories (general waste, glass, cans, plastic, and paper) using 2000 images for training, 250 for validation, and 250 for testing. Training used a batch size of 32 and a fixed number of steps (20,600) due to resource constraints. Low loss values (classification, localization, regularization, and total loss) suggest good model performance, but real-world testing is needed to con- firm accuracy. This project uses mean precision (mAP) to evaluate the accuracy of a model designed to detect general and recyclable waste items. mAP, calculated using recall values from 0 to 1 and an Intersection over Union (IoU) threshold, assesses the model’s performance across various objection models [14]. The model achieved an overall mAP of 71.25%, with "can" items showing the highest accuracy (73.88%) and "general waste" the lowest (67.49%). However, these results are based on a testing dataset and may not reflect real-world performance, necessitating further testing in real-world conditions.

The test cases involved object detection accuracy, waste level detection accuracy, Grafana visualization, and remote monitoring of the waste bins using Remote-RED. In conducting the experiment in a real-world scenario, these can waste and display their accuracy upon entering the sight of the Pi Camera. The accuracy is then computed by the deep learning model when deployed on a Raspberry Pi 4 Model B.

Table 1 presents the average classification accuracy for five waste categories: general waste, glass, plastic, cans, and paper. The "can" category exhibited the highest accuracy (90.0%), followed by general waste (87.0%), plastic (85.5%), and paper (82.5%). The glass category demonstrated the lowest accuracy (77.3%). This variation in accuracy may be attributed to several factors. The relatively high accuracy of the "can" category is likely due to its consistent cylindrical shape and metallic material, facilitating easier identification. Conversely, the lower accuracy of the "glass" category may be a consequence of its transparent nature and often irregular shapes, posing challenges for accurate recognition.

**Table 1**. The average classification accuracy

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Category | Test 1 (%) | Test 2 (%) | Test 3 (%) | Test 4 (%) | Average Precision (%) |
| General Waste | 96 | 83 | 86 | 83 | 87 |
| Glass | 90 | 61 | 78 | 81 | 77.3 |
| Plastic | 89 | 90 | 81 | 82 | 85.5 |
| Can | 96 | 87 | 88 | 89 | 90 |
| Paper | 92 | 76 | 85 | 77 | 82.5 |

The ultrasonic sensors will be tested in this section to see if the value will change and be recognized in a different way in the real world. This section seeks to assess the ultrasonic sensor’s performance in a regulated setting. Figure 3(a) shows both waste bins packed with plastic bags in a near-capacity condition. Fill level measurements from ultrasonic sensors were automatically obtained every five seconds. The trash level information from both bins is then shown on the Node-RED dashboard in Figure 3(b). The waste level detecting system worked as the recyclable trash bin showed an 81% fill level, and the general waste bin showed an 80% fill level. Grafana’s graphs show how much waste was in each bin. After five hours of leaving the garbage bins, the sensor values were collected, successfully pushed to the InfluxDB, and then shown on this Grafana platform.

A box with a label and a box with a label

AI-generated content may be incorrect.

**(a) (b)**

**FIGURE 3**. (a) The near-capacity state of both waste bins, and (b) The waste level data

# **DISCUSSIONS**

This project effectively illustrated a working smart waste management system that includes level monitoring and garbage detecting features. With a mean average precision (mAP) of 71.25% under controlled testing settings and a markedly higher accuracy of 84.46% in real-world situations, the system used a Raspberry Pi Camera for detection. This enhancement emphasizes how crucial real-world testing is for assessing how reliable such systems are. The use of ultrasonic sensors for waste level detection proved to be quite accurate with little variance, allowing for efficient real-time bin fill level monitoring. Together, garbage detection and level monitoring provide a practical tool for optimizing waste collection routes and enhancing the overall efficacy of waste management. Further study could focus on enhancing the waste detection model. Categories and investigating the integration of other sensor modalities for improved data gathering and analysis to increase accuracy across all wastes.

# **CONCLUSION**

Automated waste sorting, facilitated by AI-powered image recognition, increases recycling rates and promotes a circular economy. The data collected supports data-driven decision-making, informing resource allocation, predictive maintenance, and long-term urban planning. While challenges remain (high setup costs, sensor accuracy, data trans- mission reliability), the consensus is that IoT-enabled smart waste management systems offer a feasible and effective solution for improving efficiency, sustainability, and public health within smart cities. Further research is needed to address remaining gaps, particularly in holistic system design, real-world testing, and citizen engagement strategies.

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