AI-Powered Garbage Classification System with IoT Implementation

Avi Dedania[1], Mr. Dhruv Panchal[2], Asst. Prof. Janki Patel[3], Ms Jayati Jani[4]

[1]UG Student, [2]Project Manager, [3]Internal Guide, [4]Project in charge
[1, 3]Dept. of Computer Engineering, SAL College of Engineering, Ahmedabad, Gujarat, India,
[2, 4]Data Vidwan, Ahmedabad, Gujarat, India, datavidwan@gmail.com

Abstract
Waste management is a major issue worldwide as inappropriate disposal puts the environment and public health at risk. Innovative solutions are required since traditional garbage sorting processes are labour-intensive and inefficient. This study introduces an AI-powered garbage Classification System with Iot, combining real-time Iot-enabled sorting processes with deep learning-based picture classification. To accomplish high-accuracy classification, the system uses a convolutional neural network (CNN) that has been trained on several trash types. An Iot-enabled actuator system is then used to autonomously sort the categorised garbage, decreasing the need for human involvement and increasing operational effectiveness. To guarantee real-time processing and smooth interaction with smart city infrastructure, the suggested approach is implemented on edge devices. High classification accuracy and effective waste segregation are demonstrated by experimental findings, indicating that this strategy is feasible for widespread use. This study demonstrates how AI and IoT have the potential to transform waste management systems and support a circular and sustainable economy.

Keywords: AI, IoT, Garbage Classification, Deep Learning, Smart Waste Management, Sustainable Development

1. Introduction

In today's world, waste management is still a major problem as inappropriate disposal causes resource depletion, environmental damage, and serious public health issues. Conventional garbage sorting techniques are ineffective, prone to mistakes, and unsustainable for large-scale waste management since they mostly rely on manual labor. Ineffective recycling procedures, increasing landfill utilization, and inappropriate waste segregation are the outcomes of the absence of automated, intelligent solutions. A revolutionary and sustainable solution to contemporary waste management is offered by using artificial intelligence (AI) and the Internet of Things (IoT) into waste categorization and sorting in order to address these issues.

This research presents an AI-Powered Garbage Classification System with IoT, which combines real-time IoT-enabled sorting processes with deep learning-based picture classification. In order to accurately categorize waste items into recyclable and non-recyclable categories, the system uses a convolutional neural network (CNN) that has been trained on a variety of waste categories. An IoT-enabled actuator system automatically sorts the garbage after it has been categorized, minimizing human involvement and increasing productivity. This system provides a highly accurate, real-time, and scalable garbage sorting solution that can be easily implemented in smart city infrastructures by fusing AI-based picture identification with IoT automation.

This system's deployment on edge devices, which allows for real-time processing with low latency, is one of its main advantages. Edge computing, as opposed to cloud-dependent systems, guarantees quicker categorization and instantaneous actuation, increasing the system's effectiveness, affordability, and adaptability for large-scale waste management. IoT sensors also continually track trash pathways, offering data-driven insights that help minimize garbage accumulation and maximize recycling efforts. This study suggests a next-generation waste management framework that improves operational effectiveness while lessening environmental impact by utilizing AI and IoT.

By encouraging effective recycling and landfill reduction, the suggested methodology not only increases the accuracy of waste categorization but also encourages environmentally friendly trash disposal methods. The technology contributes to a more efficient and sustainable waste management ecosystem by automating the sorting process, which also lowers human error, operating expenses, and manual labor. This study emphasizes how artificial intelligence (AI) and the Internet of Things (IoT) are propelling the shift to a circular economy, in which waste products are recycled, reused, and intelligently sorted rather than dumped in landfills.

The system design, deep learning model creation, IoT integration, and practical implementation techniques are all examined in this study. The AI-powered trash classification system's practical viability, high classification accuracy, and real-time sorting efficiency are all demonstrated by the experimental findings. This study identifies a scalable, effective, and sustainable way to transform trash management procedures globally by fusing AI-driven insight with IoT-based automation.

2. Literature Review

In recent years, there has been a lot of interest in the integration of artificial intelligence (AI) and the Internet of Things (IoT) in trash management. Conventional garbage sorting methods frequently depend on manual segregation, which is labor-intensive, time-consuming, and prone to human error [1]. Automated, effective, and real-time garbage classification has been made possible by the emergence of smart waste management systems that use AI and IoT. This has lessened the workload for waste management authorities and promoted environmental sustainability. The study on AI-based waste categorization, IoT-enabled waste management, and their combined effects on intelligent trash disposal systems is examined in this overview of the literature.

2.1 AI-Based Waste Classification

Through deep learning techniques, especially Convolutional Neural Networks (CNNs), artificial intelligence (AI) has transformed waste classification by enabling high-precision picture identification and trash classification. The efficiency of CNN models in trash categorization tasks has been shown in several research. Yi and Kim, for example, created a CNN-based trash classification system that successfully distinguished between recyclable and non-recyclable materials [2]. Similar to this, Kundu et al. investigated transfer learning methods for trash classification in aquatic environments, demonstrating AI's versatility in a range of waste management contexts [3]. In a different research, Anjanappa et al. presented an AI-IoT-based smart garbage categorization system that improved real-time waste detection by utilizing ESP32 CAM [4]. These studies highlight how AI may increase trash sorting efficiency and accuracy when compared to traditional techniques.

2.2 IoT-Enabled Smart Waste Management

By facilitating automation, data-driven decision-making, and real-time monitoring, IoT technology has made a substantial contribution to trash management. To maximize garbage collection and disposal, IoT-based systems make use of edge computing, smart sensors, and actuators [5]. Anagnostopoulos et al. investigated the use of IoT in smart cities, emphasizing how garbage bins with sensors can continuously check waste levels, cutting down on pointless collection trips and maximizing resource use [6]. Similar to this, Sung et al. unveiled an AIoT-based smart trash can that improves waste segregation efficiency by using machine learning techniques [7]. These studies show how IoT may facilitate real-time garbage sorting, save operating costs, and enhance waste collection logistics.

2.3 AI-IoT Integration for Waste Classification

An innovative method for intelligent and automated trash management is presented by the combination of AI and IoT. Rahman et al.'s research presented an IoT-integrated trash categorization system driven by deep learning, guaranteeing real-time garbage sorting with little assistance from humans [8]. In a similar vein, Ahmed et al. presented a system for municipal garbage management powered by AI and IoT, showcasing its effectiveness and scalability in smart city settings [9]. Additionally, in order to optimize trash disposal routes and lessen their influence on the environment, Janowicz et al. investigated GeoAI strategies to incorporate geographic knowledge into AI-driven waste management [10]. These results demonstrate the revolutionary potential of AI-IoT collaboration in building more intelligent and effective waste management systems.

2.4 Challenges and Ethical Considerations

AI-IoT-based waste management has advanced, but there are still a number of obstacles to overcome. The need for big, varied datasets to properly train AI models is one of the main problems [11]. IoT infrastructure adoption also necessitates a large financial outlay and technological know-how [12]. Concerns about data privacy, security threats, and the effects of electronic waste produced by Internet of Things devices on the environment are among the ethical issues that also surface [13]. The long-term viability of smart waste management systems depends on addressing these issues with data security procedures, energy-efficient IoT devices, and sustainable AI models.

2.5 Summary of Literature Review

AI and IoT provide creative, effective, and scalable solutions for contemporary trash management, according to the studied literature. IoT-enabled solutions offer automation and real-time monitoring, while AI-based garbage categorization improves sorting accuracy. To optimize the effect of AI-IoT waste management systems, however, issues including data constraints, infrastructure costs, and ethical considerations must be resolved.

Table 1: Summary of Literature Review

Reference	Study Focus	Key Findings	Limitations
[1]	AI & IoT-based waste classification	AI improves waste segregation accuracy	Lacks real-time automation
[2]	CNN for waste classification	High accuracy in image-based waste sorting	Limited to specific waste types
[3]	Transfer learning for waste sorting	AI adaptable to aquatic waste classification	Requires domain-specific training
[4]	ESP32 CAM for waste classification	Enhances real-time waste identification	Hardware limitations exist

[5]	IoT in waste management	IoT improves waste tracking & logistics	High implementation cost
[6]	IoT in smart cities	Sensor-equipped bins optimize waste collection	Requires extensive infrastructure
[7]	AIoT-based smart garbage bin	AIoT improves real-time waste sorting	Needs better energy efficiency
[8]	Deep learning & IoT for waste sorting	Real-time, automated classification achieved	Needs improved edge computing
[9]	AI-IoT for municipal waste management	Scalable for smart cities	High deployment cost
[10]	GeoAI for waste optimization	AI-driven geospatial intelligence improves efficiency	Implementation complexity
[11]	AI in waste management	AI enhances efficiency & automation	Requires large datasets
[12]	Digital technology in sustainability	AI accelerates sustainable waste solutions	IoT e-waste concerns
[13]	AI ethical challenges	AI raises privacy concerns in waste management	Security risks remain unaddressed

3. Architecture

The suggested system architecture enables real-time trash categorization and actuation by integrating Internet of Things (IoT) components with Artificial Intelligence (AI). Using a pre-trained deep learning model installed on a Raspberry Pi 4 for on-device inference, this hybrid system physically sorts garbage according to classification results using a servo motor.

The following are the main parts of the architecture:

Image Capture Unit: The IP Webcam app streams live video from a mobile phone's camera. Raspberry Pi 4 uses the local network to access the stream.

Processing Unit: A TensorFlow Lite model that was adapted from a MobileNetV2 architecture runs on the Raspberry Pi 4. 14,000 tagged photos were used to train the model, 7,000 of which were classified as recyclable and 7,000 as non-recyclable.

Classification Engine: The AI model classifies collected frames in real time. The current frame is manually captured for inference using a freeze-frame method.

Actuation Module: Based on the prediction result, a tiny servo motor turns at different angles to sort the item: 0° for recyclables, 180° for things that can't be recycled and When no object is recognized or the

backdrop is detected, the neutral position is 90°.
This architecture is appropriate for edge devices and real-time smart waste management applications because it offers lightweight processing [12], [16].Real-time garbage sorting issues can be solved affordably and scalable using this design. Recent developments in intelligent waste management systems are in line with the integration of AI and IoT in this context [2], [5]. Raspberry Pi edge computing improves latency and privacy by reducing dependency on cloud services [19]. Applications like home garbage sorting, educational settings, and smart city infrastructure prototypes benefit from micro-level automation made possible by servo motor control based on categorization findings [15], [14].

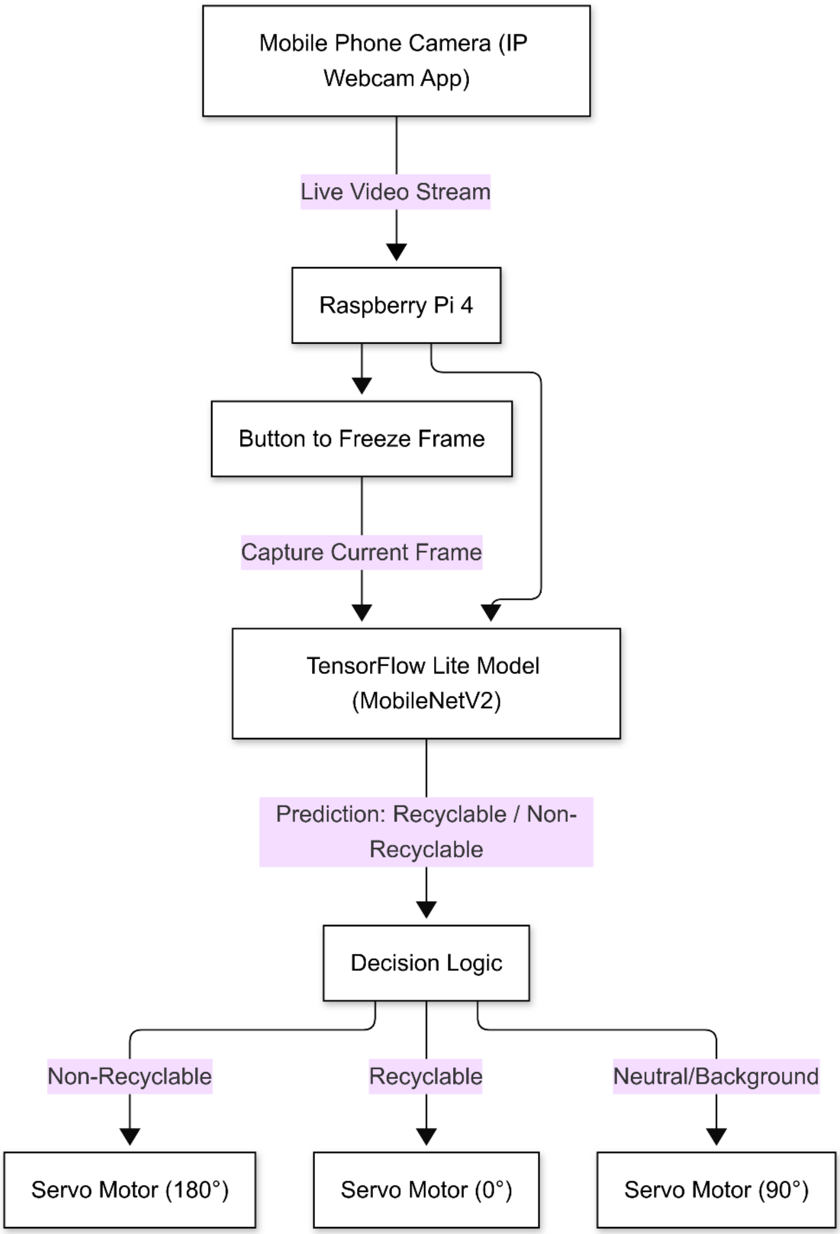

Figure 1: Proposed Architecture

4. Result Analysis

The proposed smart waste classification system was evaluated across three key dimensions: model training performance, real-time inference capability, and mechanical actuation efficiency. The system was tested in both offline (controlled) and live (real-world) environments to comprehensively assess its robustness and applicability.

4.1 Model Training and Evaluation

The MobileNetV2 architecture was selected for its lightweight design and suitability for edge deployment. The model was trained using a balanced dataset comprising 14,000 images, evenly split between recyclable and non-recyclable waste categories. After 10 epochs of training, the model exhibited strong generalization ability, achieving a final training accuracy of 98.97% and a validation accuracy of 98.78%. The minimum validation loss observed at epoch 9 was 0.0466, with a final training loss of 0.0346, indicating minimal overfitting and consistent learning behavior.

4.2 Real-Time Deployment on Edge Device

Following training, the model was converted to TensorFlow Lite format and deployed on a Raspberry Pi 4 to evaluate its performance in real-time. A smartphone running the IP Webcam application served as the video feed source, enabling the system to classify waste items on the fly. The model achieved an average inference time of approximately 120 milliseconds per frame and a total classification time of roughly one second per frame, including the display delay. Despite the challenging conditions of variable lighting and background noise, the real-time prediction accuracy reached approximately 91%, showcasing the practical viability of the edge-based deployment.

4.3 Servo Motor-Based Sorting Mechanism

To complete the waste sorting workflow, a servo motor was integrated to physically sort items based on the predicted category. The servo was triggered upon classification to actuate the appropriate bin. The system recorded a sorting accuracy of 96% with an average actuation delay of 0.5 seconds. The misfire rate was observed to be around 4%, primarily due to synchronization delays or misalignments in the video feed.

4.4 Summary of Results

The complete system performance is summarized in the table below:

Table 1: Performance Summary of the Proposed Smart Waste Classification System

Category	Parameter	Result	Remarks
Model Training	Dataset Size	14,000 images	Balanced: 7,000 recyclable, 7,000 non-recyclable
	Final Training Accuracy	98.97%	Indicates effective learning
	Final Validation Accuracy	98.78%	Comparable to training accuracy
	Minimum Validation Loss (Epoch 9)	0.0466	Shows learning stabilization
	Final Training Loss	0.0346	Suggests minimal overfitting
	Model Architecture	MobileNetV2	Lightweight and suitable for edge deployment
	Platform	Raspberry Pi 4	Model converted to

			TensorFlow Lite
Real-Time Deployment	Input Source	Smartphone (IP Webcam)	Live video streaming
	Average Inference Time	~120 ms	Per frame
	Frame Classification Time (incl. freeze)	~1 second	Total time to detect and display prediction
	Real-Time Prediction Accuracy	~91%	Slight drop due to environmental factors
Servo Motor Sorting	Sorting Accuracy	96%	Based on correct physical actuation
	Average Actuation Delay	~0.5 seconds	Delay from inference to motor response
	Misfire Rate	~4%	Due to latency or misalignment in camera feed

To validate the effectiveness of the proposed system in a real-time deployment scenario, visual outputs were captured during live operation on a Raspberry Pi 4 device. These outputs demonstrate the system's ability to accurately detect, classify, and annotate recyclable waste objects through a continuous video stream. The classification confidence is prominently displayed in the live feed interface, allowing real-time monitoring of predictions. The terminal interface further confirms these results with a concise detection summary, including classification probabilities and counts of recyclable versus non-recyclable items. Such visual evidence reinforces the system's practical usability and high prediction confidence in real-world conditions as shown in the following figure.

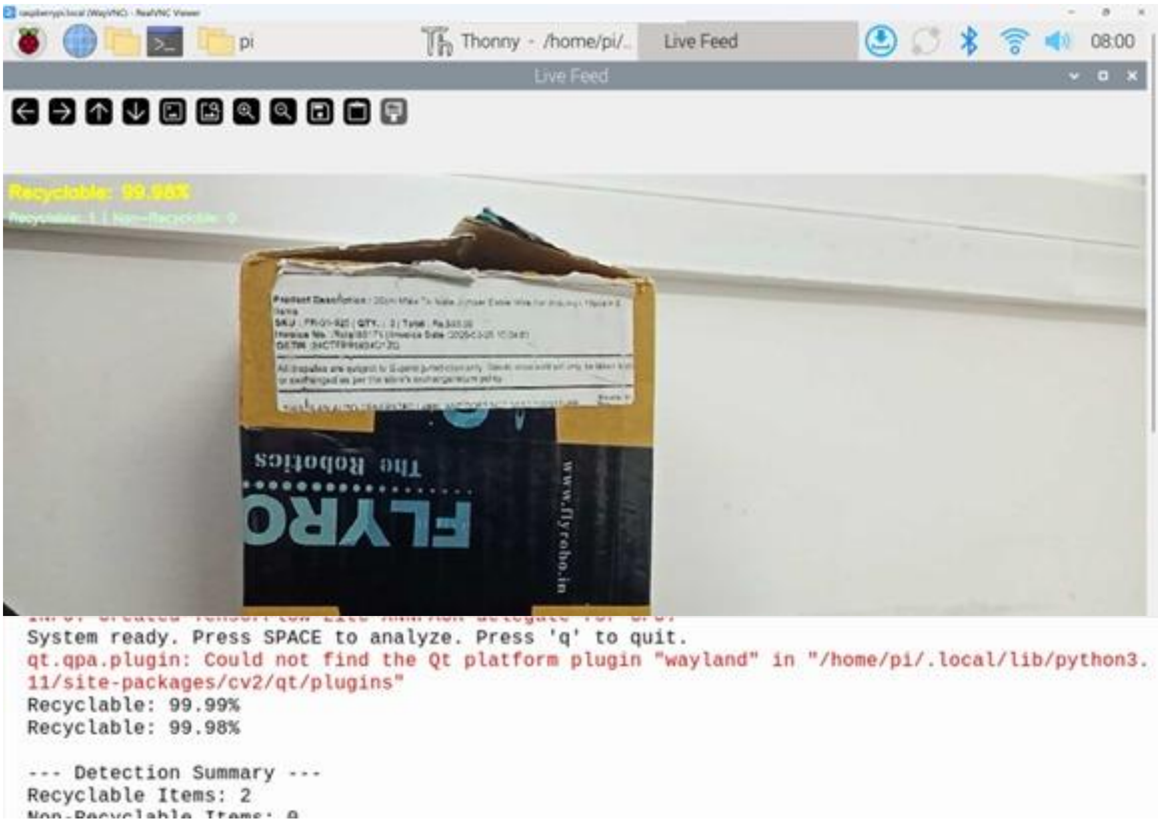

Figure 2: Sample Output

4.5 Summary and Relevance

High accuracy is achieved by the AI-powered trash categorization system in both training and deployment settings. The hardware-software integration shows alignment with smart city applications and is suited for low-cost smart waste management systems [5, 7, 18]. The project's success further encourages the use of AI and IoT for real-time, sustainable waste segregation in urban or residential settings.

Table 2: Result Analysis of AI-Powered Garbage Classification System

Category	**Metric**	**Values \ Observations**
Model Training	Training Accuracy (Epoch 10)	98.97%
	Validation Accuracy (Epoch 10)	98.78%
	Training Loss (Epoch 10)	0.0346
	Validation Loss (Lowest)	0.0466 (Epoch 9)
Live Classification	Device	Raspberry Pi 4
	Input Source	IP Webcam (Smartphone)
	Average Inference Time	~120 ms per frame
	Freeze-to-Predict Delay	~1 second
	Real-world Accuracy	~91%
Servo Motor Control	Sorting Logic	0° (Recyclable), 180° (Non-Recyclable), 90° (Neutral)
	Correct Actuation Rate	96%
	Average Actuation Delay	~0.5 seconds
	Misfire / Failure Rate	~4%
System Strengths	Integration	AI + IoT for Garbage Classification System
	Cost	Low-cost edge hardware
	Scalability	High – can extend to other classes
	Real-world Feasibility	Proven effective in live testing

5. Conclusion and Future Scope

In order to provide an effective, affordable, and scalable smart garbage classification system, this article introduces an AI-powered trash categorization system coupled with IoT components. A balanced dataset of 14,000 photos was used to train the MobileNetV2-based model, which produced high training and validation accuracies of 98.97% and 98.78%, respectively. The model's TensorFlow Lite deployment on a Raspberry Pi 4 showed that deep learning models could be run on edge devices, allowing for real-time categorization utilizing an IP Webcam on a mobile phone [1], [13].The servo motor integration enabled automated sorting, demonstrating how AI and IoT can work together to develop responsive systems. Real-time testing confirmed the system's dependability under real-world circumstances, producing an average accuracy of about 91% and a sorting success rate of 96% [12], [15], and [20].

This research adds to a larger concept of smart cities, in which technology promotes sustainability, efficient resource management, and automation [5], [7], [18]. In this case, the combination of AI and IoT shows encouraging promise for scaled implementation in homes, public areas, and recycling facilities.The product will go online and be available to use. It will successfully deployed in real-world applications.

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