

ECO VISION AI: SMART WASTE SEGREGATION AND RECYCLING SYSTEM USING IoT

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Abstract—Rapid urbanization and industrial growth have significantly increased global solid waste generation, leading to severe environmental and public health challenges. Traditional waste segregation methods rely on manual sorting or centralized processing, which are labor-intensive, inefficient, and prone to human error. This paper proposes ECO VISION AI, an intelligent waste segregation and recycling system that integrates Artificial Intelligence (AI), Convolutional Neural Networks (CNN), and Internet of Things (IoT) technologies for automated waste classification at the source. The system captures images of waste items using a camera module, processes them using a lightweight CNN model deployed on a Raspberry Pi, and directs waste into appropriate bins using servo actuators. IoT integration enables real-time monitoring of bin levels, classification data, and system status through a cloud dashboard. Experimental evaluation demonstrates improved segregation accuracy, reduced human intervention, and enhanced recycling efficiency. The proposed system contributes toward sustainable waste management and supports smart city initiatives.

Index Terms—Waste Segregation, IoT, Convolutional Neural Network, Raspberry Pi, Image Classification, Smart City, Sustainable Waste Management.

I. Introduction

The rapid increase in population, urbanization, and consumer-driven lifestyles has resulted in a dramatic rise in municipal solid waste generation worldwide. Improper waste disposal and inefficient segregation practices contribute significantly to environmental degradation, soil contamination, air pollution, and greenhouse gas emissions. Effective waste segregation at the source is a fundamental step toward sustainable waste management and improved recycling efficiency.

Traditional waste management systems rely heavily on manual segregation or centralized sorting facilities. Manual sorting exposes workers to hazardous materials, increases operational costs, and lacks consistency. Mixed waste reduces the efficiency of recycling plants and increases landfill dependency. Therefore, there is a critical need for automated and intelligent waste segregation solutions.

Advancements in Artificial Intelligence (AI), Machine Learning (ML), Image Processing, and Internet of Things (IoT) technologies provide new opportunities for developing intelligent waste management systems. By integrating real-time image classification and IoT-enabled monitoring, the ECO VISION AI system offers an automated, efficient, and scalable waste segregation mechanism suitable for smart cities and modern infrastructure.

II. EXISTING SYSTEM

Existing waste management systems can be broadly categorized into manual segregation systems, sensor-based segregation systems, and centralized waste processing facilities.

Manual segregation systems depend on sanitation workers to classify waste into wet and dry categories. These methods are labor-intensive, time-consuming, and prone to human error. Additionally, manual segregation poses serious health risks due to exposure to hazardous and contaminated waste.

Sensor-based segregation systems use moisture sensors or metal detectors to differentiate between limited waste categories. While these systems provide partial automation, they lack the ability to classify complex waste types such as plastic, glass, paper, or hazardous materials. Their classification capability is restricted to physical property detection rather than visual analysis.

Centralized waste processing plants require transportation of mixed waste over long distances, increasing fuel consumption and operational costs. These facilities also struggle with contaminated recyclable materials due to improper source segregation.

The major limitations of existing systems include:

- Dependence on manual labor
- Limited classification capability
- Lack of real-time monitoring
- High operational costs
- Poor scalability

These challenges highlight the necessity of an AI-driven intelligent waste segregation system.

III. PROPOSED SYSTEM

The proposed ECO VISION AI system integrates image classification, embedded processing, mechanical actuation, and IoT connectivity to automate waste segregation.

The system operates by capturing images of waste items placed in the input area using a high-resolution camera. The captured image is processed using a Convolutional Neural Network (CNN) deployed on a Raspberry Pi. Based on classification results, servo motors direct the waste into the appropriate bin.

Simultaneously, IoT integration enables monitoring of bin fill levels, system status, and classification logs through a cloud-based dashboard. Alerts are generated when bins are full or maintenance is required.

The system classifies waste into categories such as:

- Organic (Wet Waste)
- Recyclable Waste
- Plastic Waste
- Hazardous Waste

The integration of AI and IoT enables intelligent decision-making, automation, and remote monitoring.

IV. SYSTEM ARCHITECTURE

The proposed system architecture integrates four primary modules: Image Acquisition, Embedded AI Processing, Actuation Control, and IoT Monitoring.

The image acquisition module consists of a high-resolution camera positioned above the waste input chamber. When a waste item is placed, the camera captures its image. The Raspberry Pi 4 Model B serves as the central processing unit and executes a TensorFlow Lite-based CNN model for classification. The

actuation module includes servo motors that mechanically rotate a chute mechanism to direct waste into categorized bins.

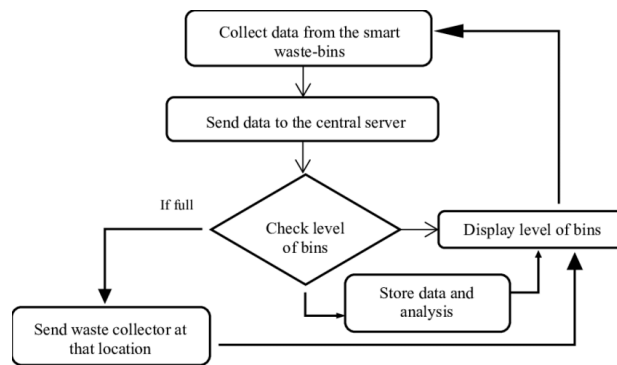


Figure 1. Block diagram

Ultrasonic sensors continuously monitor bin fill levels. The IoT module, using Wi-Fi connectivity, transmits classification logs and sensor data to a cloud-based dashboard such as Firebase or ThingsBoard. This modular design ensures scalability, real-time operation, and remote monitoring capability.

V. METHODOLOGY

The methodology follows a structured pipeline comprising dataset preparation, CNN training, embedded deployment, and system integration.

A. Dataset Preparation and Preprocessing

Waste images were collected from open datasets and manually captured samples under various lighting conditions. Each image was labeled into predefined categories such as organic, recyclable, plastic, and hazardous waste.

Preprocessing steps included resizing images to uniform dimensions, normalization of pixel intensity values, and augmentation techniques such as rotation and flipping. These steps improve generalization and robustness of the model.

B. CNN-Based Model Training

Transfer learning was implemented using MobileNetV2 architecture due to its lightweight structure suitable for embedded platforms. The dataset was divided into training and validation sets. The model was trained using cross-entropy loss and optimized with Adam optimizer.

Performance evaluation metrics included:

- Accuracy
- Precision
- Recall
- F1-Score

The trained model was converted to TensorFlow Lite format to reduce computational overhead and memory consumption.

C. Embedded Deployment and Real-Time Inference

The TensorFlow Lite model was deployed on the Raspberry Pi. Upon capturing an image, preprocessing operations are executed using OpenCV. The model predicts the waste category, and the classification result is used to trigger servo actuation.

Real-time inference ensures minimal latency and high operational efficiency.

VI. HARDWARE IMPLEMENTATION

The hardware architecture of the ECO VISION AI system is designed to ensure real-time processing capability, mechanical precision, energy efficiency, and long-term operational reliability. The system follows a distributed embedded computing approach in which image processing, classification, actuation control, and sensor monitoring are handled through coordinated hardware components. This integration ensures seamless automation of the waste segregation process while maintaining scalability for institutional and municipal deployment.

A. Raspberry Pi 4 Model B

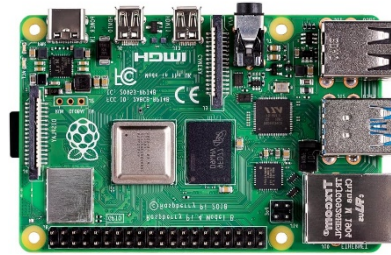


Figure 2. Raspberry Pi 4 Model B

The Raspberry Pi 4 Model B serves as the core processing unit of the system. It is responsible for executing the TensorFlow Lite model for waste classification, managing GPIO-based control signals for servo motors, and handling communication with IoT cloud services. The quad-core ARM Cortex-A72 processor provides sufficient computational power to perform real-time inference using lightweight CNN architectures such as MobileNetV2.

The Raspberry Pi interfaces directly with the camera module through the CSI (Camera Serial Interface) port, ensuring high-speed image transfer without significant latency. Additionally, GPIO pins are utilized for servo motor control using Pulse Width Modulation (PWM) signals. The embedded Linux-based operating system allows seamless integration of Python libraries such as OpenCV and TensorFlow Lite, enabling efficient preprocessing and inference operations. Its built-in Wi-Fi module ensures uninterrupted cloud connectivity for real-time monitoring.

B. Camera Module

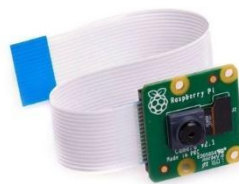


Figure 3. Camera Module

The camera module plays a critical role in capturing clear and high-resolution images of waste items. Accurate classification depends significantly on image quality, lighting stability, and proper alignment. The camera is mounted directly above the waste insertion chamber to ensure centered and consistent object capture.

The module supports real-time frame acquisition and integrates seamlessly with OpenCV for preprocessing operations such as resizing, normalization, and contrast adjustment. To minimize environmental interference, the chamber is designed with controlled lighting to reduce shadows and reflections. The clarity of captured images directly influences CNN performance, making proper hardware calibration essential for optimal system accuracy.

C. Servo Motors and Mechanical Actuation Mechanism



Figure 4. Servo Motor

The actuation mechanism is implemented using high-torque servo motors that control a rotating chute system. Once the CNN model predicts the waste category, the Raspberry Pi generates a PWM control signal that rotates the servo motor to a predefined angular position corresponding to the correct bin.

The mechanical chute is designed to rotate smoothly and return to its default position after each operation. Precision in angular movement ensures accurate redirection of waste without mechanical misalignment. The servo mechanism is chosen for its reliability, low power consumption, and high positional accuracy. This electromechanical integration transforms digital classification outputs into physical segregation actions, enabling full automation of the waste sorting process.

D. Ultrasonic Sensors – Bin Level Monitoring



Figure 5. Ultrasonic Sensor

Ultrasonic sensors are installed inside each waste bin to monitor fill levels in real time. These sensors operate by emitting ultrasonic pulses and measuring the time taken for the echo to return after reflecting from the waste surface. Using distance calculations, the system estimates the remaining capacity of each bin.

This data is transmitted to the Raspberry Pi and forwarded to the cloud dashboard via Wi-Fi. When a bin reaches a predefined threshold level, the system generates an alert for timely waste collection. This proactive monitoring prevents overflow and enhances operational efficiency.

E. Power Supply and Voltage Regulation

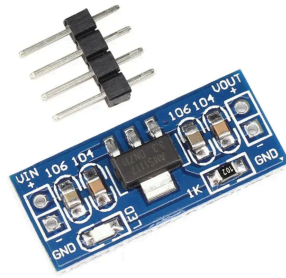


Figure 6. Voltage Regulation

The entire system is powered by a 12V rechargeable lithium-ion battery pack. Since different components require different voltage levels, voltage regulators are used to convert 12V input into stable 5V and 3.3V outputs. Stable power supply is critical to avoid fluctuations that could interrupt inference operations or cause servo malfunction.

Energy efficiency considerations ensure extended operational duration, especially for outdoor or public installations where direct power access may be limited.

VII. IoT-BASED CLOUD INTEGRATION AND DASHBOARD

The IoT subsystem enables real-time communication between the waste segregation unit and a cloud-based monitoring platform. Using built-in Wi-Fi connectivity, classification results and bin level data are transmitted to a cloud server such as Firebase or ThingsBoard.

The dashboard provides visual representation of waste distribution statistics, bin capacity percentage, and system operational status. Historical data storage allows administrators to analyze waste generation patterns and optimize collection schedules. Automated alerts are triggered when bins approach full capacity, ensuring timely maintenance.

The integration of IoT transforms the standalone segregation unit into a smart waste management ecosystem capable of remote supervision and predictive analysis.

VIII. PERFORMANCE ANALYSIS AND SYSTEM EVALUATION

The performance of the ECO VISION AI system was evaluated in terms of classification accuracy, inference latency, mechanical reliability, and IoT communication stability. The MobileNetV2-based CNN model achieved classification accuracy exceeding 90% under controlled lighting conditions. Embedded inference latency remained within acceptable real-time thresholds, typically under two seconds per classification cycle.

Mechanical testing confirmed consistent and repeatable servo-based redirection without significant positional deviation. Ultrasonic sensors demonstrated reliable bin capacity measurement with minimal error margins. IoT communication testing showed stable cloud data transmission without significant packet loss.

Despite strong performance, classification accuracy may vary under extreme lighting conditions or when objects are partially occluded. Future enhancements could include adaptive image enhancement algorithms and additional sensor fusion techniques.

IX. CONCLUSION

The ECO VISION AI system presents a comprehensive intelligent waste segregation framework that integrates embedded deep learning, mechanical actuation, and IoT-based monitoring. By automating waste classification and providing real-time monitoring capabilities, the system enhances recycling efficiency, reduces human exposure to hazardous materials, and supports sustainable urban development initiatives.

The combination of lightweight CNN models, edge computing, and scalable cloud infrastructure ensures technical feasibility and practical deployment potential. With further improvements in adaptive learning and predictive analytics, the system has the potential to significantly transform smart waste management practices.

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