



DESIGN AND DEVELOPMENT OF AN INTELLIGENT SMART RECYCLING BIN

USING ARTIFICIAL INTELLIGENCE FOR AUTOMATED WASTE CLASSIFICATION

1.INTRODUCTION & RESEARCH GAP

Recycling contamination can occur when waste is incorrectly disposed of, and conventional recycling bins rely heavily on users making the correct recycling decision.

Smart waste-management technologies have introduced sensors, IoT monitoring and Artificial Intelligence; however, many systems primarily focus on bin capacity, collection and logistics rather than assisting the recycling decision at the point of disposal.

Research Gap: This project addresses the need for an affordable integrated prototype that combines object detection, AI-based waste classification, automated lid control and digital monitoring within a single smart recycling system.

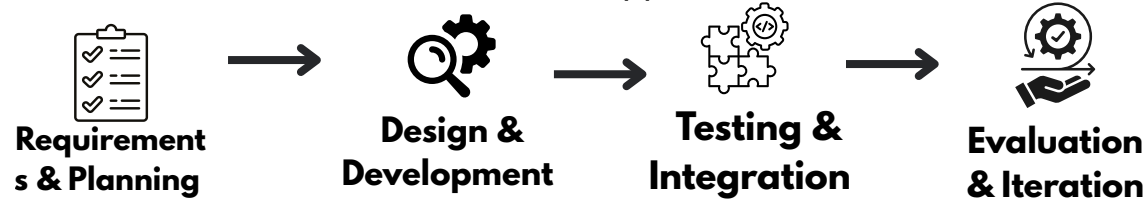
2.Aim & Objectives

Aim: To design, develop and experimentally evaluate an Intelligent AI-Based Smart Recycling Bin capable of identifying recyclable and non-recyclable waste and automatically controlling the bin lid according to the classification result.

- Objectives:**
- Review existing research on Artificial Intelligence, Computer Vision, Embedded Systems, IoT and intelligent waste management.
- Design and develop a functional prototype integrating a Raspberry Pi 4, Arduino Uno, camera, two HC-SR04 ultrasonic sensors and servo motor.
- Implement AI-based waste classification to distinguish between recyclable and non-recyclable waste.
- Develop a monitoring dashboard to record and display classification results, confidence scores and recycling activity.
- Experimentally evaluate the functionality, response time and integrated operation of the completed prototype.

3.Methodology

Pragmatic philosophy → Experimental Product Development with Agile-inspired iterative approach.



Tools & Technologies

Hardware: Raspberry Pi 4, Arduino Uno, HC-SR04, Picamera2 (Camera Module), Servo Motor.

Software: Python, Picamera2, OpenCV, NumPy, TensorFlow/Keras (EfficientNet preprocessing), ONNX Runtime, PySerial, Flask, JSONL.

Model: best_model_EfficientNetB0_20260720_175329.onnx (Binary Classification)

Data Storage: JSON Lines (sorting_log.jsonl, fill_level.jsonl)

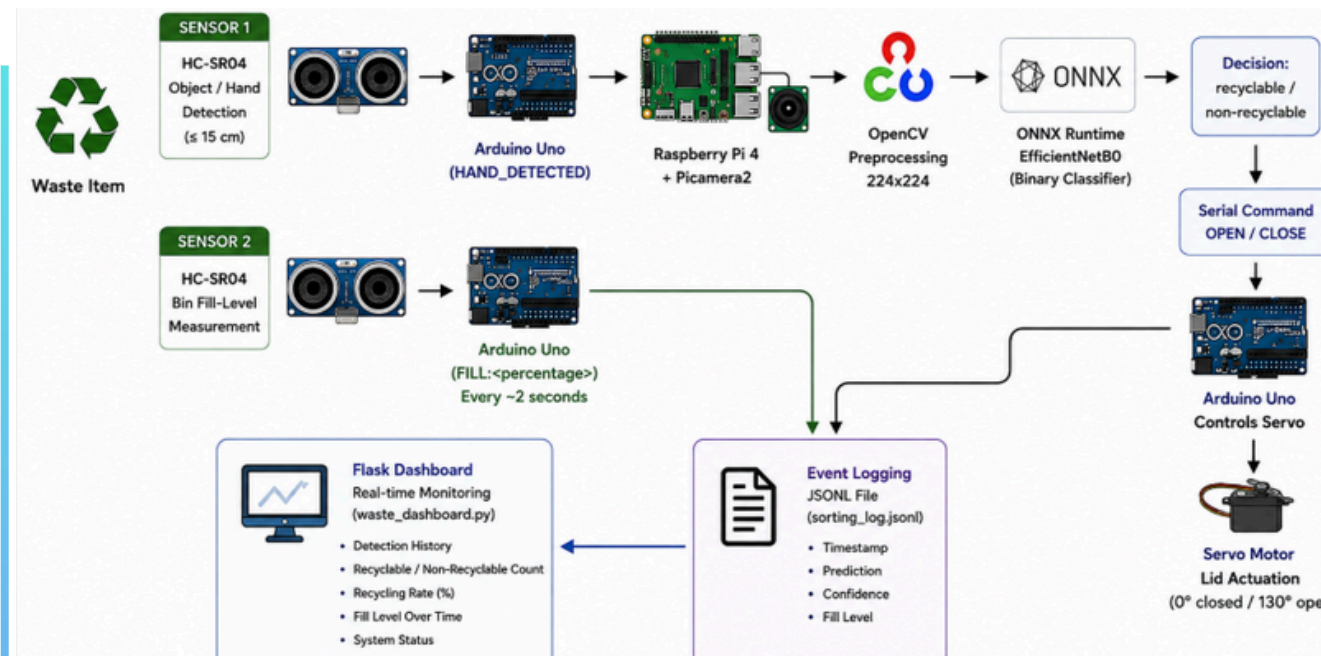
Dashboard: Flask application (waste_dashboard.py)

Main Application: main.py

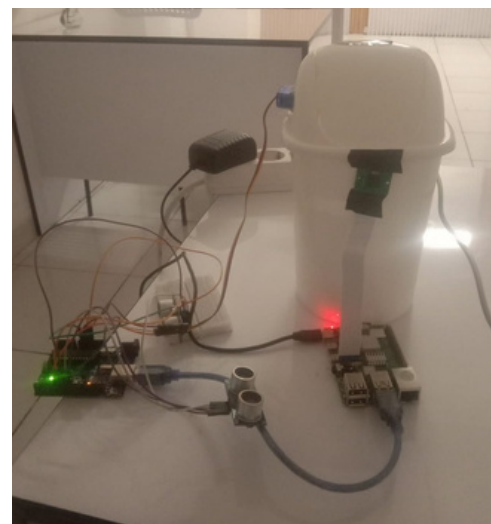
Classification: Recyclable / Non-Recyclable

Decision Threshold: 0.50

4.OVERALL ARCHITECTURE



4.1 REAL PROTOTYPE(PHYSICAL IMPEMANTATION)



Key Implementation Details

HC-SR04 Sensor 1: Detects the presence of a waste item/hand within 15 cm and initiates the classification process.

HC-SR04 Sensor 2: Measures the distance to waste inside the bin to estimate the bin fill level.

Arduino Uno: Handles ultrasonic sensing, communicates with the Raspberry Pi and controls the servo motor.

Raspberry Pi 4 + Picamera2: Captures the waste image and runs the AI classification process.

OpenCV: Preprocesses and resizes captured images to 224 × 224 pixels before classification.

ONNX Runtime: Executes the deployed EfficientNetB0 binary classification model to classify waste as Recyclable or Non-Recyclable.

Servo Motor: Automatically controls the bin lid according to the classification result (OPEN/CLOSE).

Data Logging: Classification results, confidence scores and timestamps are recorded using JSONL.

Flask Dashboard: Provides monitoring of detection history, recyclable/non-recyclable counts and recycling activity.

4.2 COMUNICATION PORTOCOL

Arduino → Raspberry Pi	Raspberry Pi → Arduino	Arduino → Raspberry Pi (Fill Level)	Connection
HAND_DETECTED (Object/hand detected)	OPEN (Open lid to 130°) CLOSE (Close lid to 0°)	FILL:<percentage> (Fill level every ~2 s)	Serial Port: /dev/ttyACM0 Baud Rate: 9600

4.3 DATA FLOW



5.RESULTS (BASED ON DASHBOARD DETECTIONS)

5.1 DASHBOARD DETECTIONS SUMMARY (OPERATIONAL DATA)



5.2 SYSTEM PERFORMANCE (INTEGRATED TESTING)



Functional Outcomes

- ✓ Object/hand detection successfully triggered the classification process using HC-SR04 Sensor 1.
- ✓ The Raspberry Pi camera captured the waste item for image processing and classification.
- ✓ The ONNX Runtime binary classifier classified detected items as Recyclable or Non-Recyclable.
- ✓ OPEN/CLOSE serial commands enabled the Arduino Uno to control the servo-operated bin lid according to the classification result.
- ✓ Classification results were recorded using JSONL event logging and displayed through the Flask monitoring dashboard.
- ✓ HC-SR04 Sensor 2 measured the distance to waste inside the bin to support fill-level monitoring.

6.DISCUSSION

DISCUSSION

Strengths

Integrated hardware–software system with real-world interaction.
Local AI inference using ONNX – no cloud dependency.
Automatic decision and physical response.
Real-time monitoring dashboard with history and statistics.

Limitations

Deployed model is binary (recyclable / non-recyclable) only.
Dataset size and environmental variety are limited.
Fill-level readings (FILL:<percentage>) are not currently logged to JSONL by main.py.
Five integration trials – short-term evaluation.

7.CONCLUSION

This project successfully developed a functional AI-based smart recycling bin integrating Computer Vision, embedded hardware and automated lid control. The prototype demonstrates that Raspberry Pi, Arduino, ultrasonic sensing and ONNX-based classification can work together to identify waste as recyclable or non-recyclable, provide an appropriate physical response and record recycling activity through a monitoring dashboard. Overall, the system provides a successful proof of concept and a strong foundation for future development and real-world testing.

References

- Longo, E., Sahin, F.A., Redondi, A.E.C., Bolzan, P. and Bianchini, M. (2022) 'A 5G-enabled smart waste management system for university campus', Sensors, 22(21), 8278.
- Adedeji, O. and Wang, Z. (2019) 'Intelligent waste classification system using deep learning convolutional neural network', Procedia Manufacturing, 35, pp. 607–612.
- Tan, M. and Le, Q.V. (2019) 'EfficientNet: Rethinking model scaling for convolutional neural networks', Proceedings of the 36th International Conference on Machine Learning, 97, pp. 6105–6114.
- Bradski, G. (2000) 'The OpenCV Library', Dr. Dobb's Journal of Software Tools.
- Raspberry Pi Ltd. (2026) Raspberry Pi Documentation. Available at: Raspberry Pi Documentation
- Arduino (2026) Arduino Documentation. Available at: Arduino Documentation
- ONNX Runtime (2026) ONNX Runtime Documentation. Available at: ONNX Runtime Documentation