DESIGN AND DEVELOPMENT OF
"IoT & ML-Based Smart Waste Management System"

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AUGUST 2025

DECLARATION

We hereby declare that this project has been done by us under the supervision of **Indrojit Sarkar**, Lecturer, Department of CSE, Daffodil International University. We also declare that neither this project nor any part of this project has been submitted elsewhere for the award of any degree or diploma.

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ACKNOWLEDGEMENT

First, we express our heartiest thanks and gratefulness to almighty God for His divine blessing makes it possible to complete the project successfully.

We are really grateful and wish to express our profound indebtedness to Indrojit Sarkar, Lecturer, Department of CSE, Daffodil International University, Dhaka. Deep Knowledge & keen interest of our supervisor in the field of "Embedded Systems and IoT" to carry out this project. His endless patience, scholarly guidance, continual encouragement, constant and energetic supervision, constructive criticism, valuable advice, reading many inferior drafts and correcting them at all stages have made it possible to complete this project.

We would like to express our heartiest gratitude to Professor Dr. Sheak Rashed Haider Noori, Head, Department of CSE, for his kind help to finish our project, and also to other faculty members and the staff of the CSE department of Daffodil International University.

We would like to thank our entire course mates in Daffodil International University, who took part in this discussion while completing the coursework.

Finally, we must acknowledge with due respect the constant support and patience of our parents.

ABSTRACT

Effective waste segregation is one of the major challenges in modern urban environments. Conventional waste disposal systems rely heavily on manual sorting, which is inefficient, time-consuming, and often inaccurate. This project proposes a **Smart Waste Management System** that leverages IoT and machine learning to automate the process of waste classification and disposal. The system is built using an Arduino Uno, ESP32-CAM, stepper and servo motors, ultrasonic sensor, PIR sensor, and rain sensor integrated into a multi-bin setup. When a user places waste into the input cup, the ESP32-CAM captures an image and transmits it to a trained machine learning model running on a computer for classification. Based on the detected waste type (e.g., plastic, organic, paper, metal), the Arduino controls the stepper and servo motors to rotate the bin selector and deposit the waste into the appropriate compartment. Additionally, the rain sensor distinguishes between dry and wet waste, while the PIR sensor detects user presence and the ultrasonic sensor monitors bin capacity. By combining **sensors, computer vision, and embedded control**, the system enables efficient, contactless, and automated waste segregation. This smart solution reduces human involvement, improves recycling accuracy, and contributes toward sustainable urban waste management.

1. Introduction

Waste management has become a critical challenge in modern societies due to rapid urbanization, industrialization, and population growth. Traditional methods of waste collection and segregation are mostly manual, leading to inefficiency, increased labor costs, and frequent errors in classification. Improper segregation of waste not only affects the recycling process but also poses serious threats to the environment and public health. To address these challenges, automation and smart technologies are being increasingly explored in the field of waste management.

Recent advances in the **Internet of Things (IoT)** and **Artificial Intelligence (AI)** have opened new opportunities for developing intelligent waste management systems. IoT enables real-time monitoring and communication between devices, while AI provides powerful tools for data-driven decision-making, such as waste classification through image recognition. By combining these technologies with sensors and electromechanical systems, it is possible to design an efficient, automated, and sustainable solution for waste segregation.

This project proposes an **IoT-Based AI-Powered Multi-Sensor Smart Waste Management System with Automated Bin Selection**. The system integrates multiple sensors including an ultrasonic sensor for bin capacity monitoring, a PIR sensor for user detection, and a rain sensor to distinguish between wet and dry waste. An **ESP32-CAM** captures images of waste items and sends them to a trained AI model running on a computer for classification. Based on the classification result, the **Arduino Uno** controls a stepper motor and servo motor to automatically rotate and open the appropriate bin compartment, ensuring proper disposal of the waste.

By automating the waste segregation process, this system reduces human involvement, minimizes errors, and enhances the efficiency of recycling. Furthermore, it contributes to the development of sustainable smart cities by promoting eco-friendly and technologically driven waste management practices.

2. Objectives

The primary objective of this project is to design and implement an **IoT-Based AI-Powered Multi-Sensor Smart Waste Management System with Automated Bin Selection** that ensures efficient and automated waste segregation. The specific objectives are as follows:

1. **To develop an automated waste segregation system** that minimizes human intervention and reduces errors in waste classification.

2. **To integrate multiple sensors** (ultrasonic, PIR, and rain sensor) for real-time detection, monitoring, and accurate classification of waste conditions.

3. **To implement AI-based image recognition** using the ESP32-CAM for identifying different categories of waste.

4. **To design an automated bin selection mechanism** using servo and stepper motors for proper disposal of classified waste.

5. **To establish IoT communication** for transmitting data between the hardware components and the computer for AI processing.

6. **To enhance waste management efficiency** by reducing manual effort, improving accuracy, and promoting eco-friendly practices.
7. **To contribute toward sustainable smart city development** through the adoption of advanced technologies in waste management.

3. Components Used

The proposed IoT-Based AI-Powered Multi-Sensor Smart Waste Management System integrates hardware, sensors, and software components to achieve automated waste segregation. The components used in this project are as follows:

1. Microcontrollers & Modules

- Arduino Uno – Main controller for managing sensors and motors.
- ESP32-CAM – Captures images of waste items and sends them to the AI model for classification.

2. Motors

- Stepper Motor (28BYJ-48 with ULN2003 driver) – Rotates the bin disc to align the correct waste compartment.
- Servo Motor (SG90/MG995) – Controls the bin door for dropping the waste.

3. Sensors

- Ultrasonic Sensor (HC-SR04) – Monitors bin capacity to detect if the bin is full.
- PIR Motion Sensor – Detects user presence at the waste input.
- Rain Sensor – Differentiates between wet and dry waste.

4. Power Supply

- 5V Battery / Power Bank – Powers motors and ESP32-CAM.
- Arduino USB or 9V Adapter – Powers Arduino Uno.

5. Supporting Components

- Jumper wires, breadboard, resistors (for voltage divider if needed), and connectors.
- 4-compartment bin setup – Holds different types of waste.
- Cup (input container) – Houses sensors and receives waste from the user.

6. Software

- Arduino IDE – Programming environment for Arduino Uno and ESP32-CAM.
- Python 3.x – Running the AI model for waste classification.
- TensorFlow/Keras – Machine learning library for training the waste classifier.
- OpenCV – Image processing library.
- Flask – Web server to receive images and send classification results to Arduino.

4.1 Block Diagram

The block diagram shows how the ESP32 NodeMCU connects with sensors, display, and actuator. The MAX30100, DS18B20, and MPU6050 sensors collect health and activity data, which is processed by the ESP32 and shown on the TFT display. The vibration motor provides alerts, while a rechargeable 18650 Li-Ion battery powers the system.

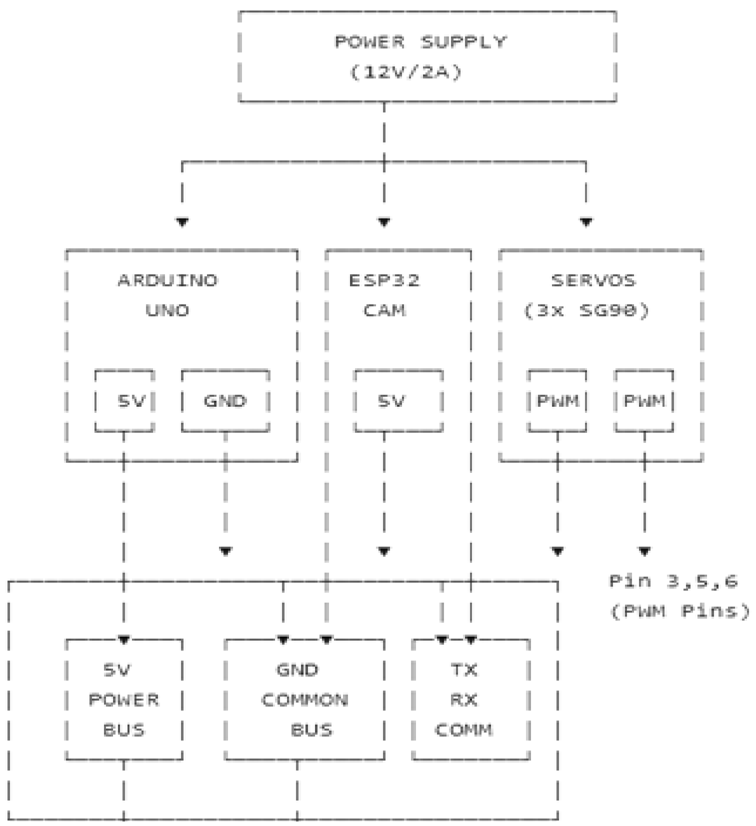


Fig 4.1: System Work Flow

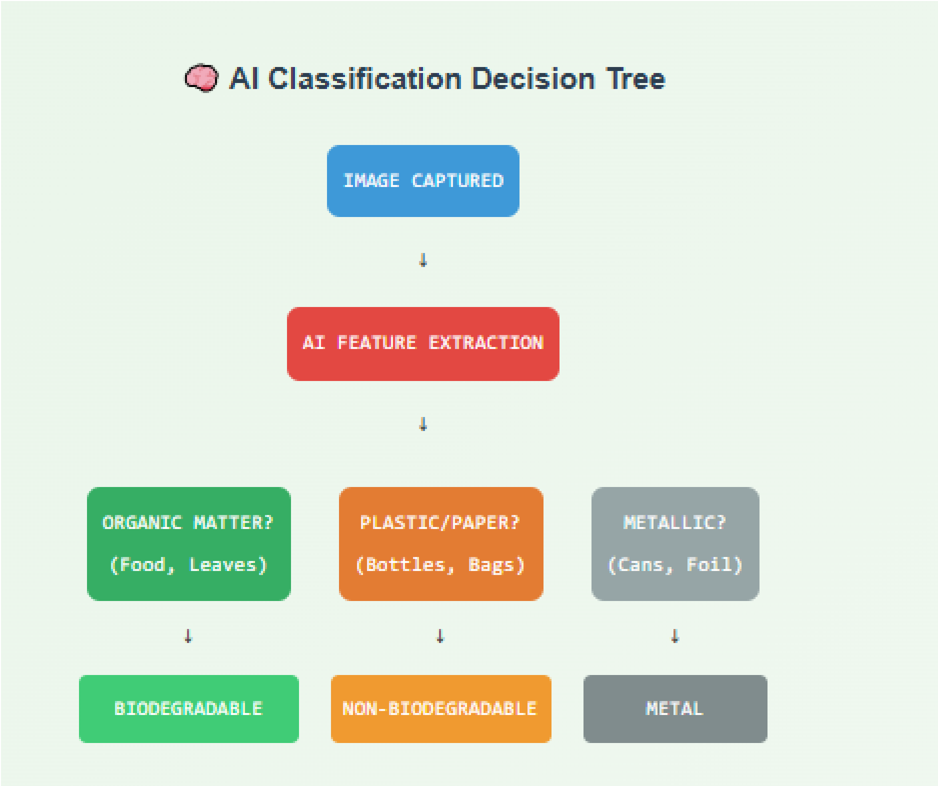


Fig 4.2: Classification tree

System Design:

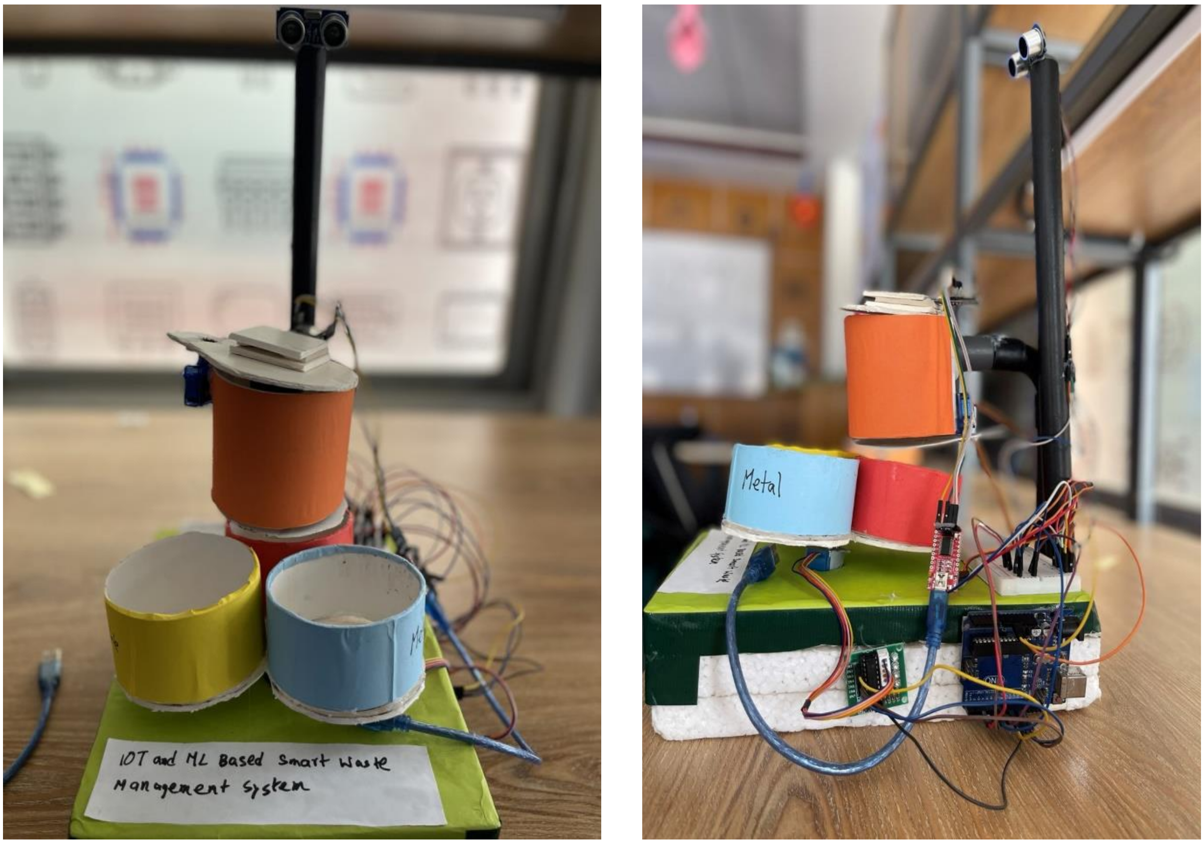


Fig 4.3: Project Image

4.2 Software Design

The software design of the IoT-Based AI-Powered Multi-Sensor Smart Waste Management System integrates embedded programming, image processing, machine learning, and IoT communication to automate waste segregation. The design can be divided into several modules, each responsible for a specific function.

1. ESP32-CAM Module

Function: Captures images of waste items and sends them to the AI server for classification.

Software Flow:

- Initialize camera and WiFi connection.
- Wait for user interaction (PIR sensor triggers).
- Capture image of the waste item.
- Send the image via HTTP POST request to the Flask server running the AI model.
- Receive the predicted waste type and forward it to the Arduino Uno via UART.

2. AI Classification Module (PC/Server)

Function: Classifies waste images into categories such as plastic, paper, metal, and organic.

Software Flow:

- Receive image from ESP32-CAM via Flask API.
- Preprocess image (resize, normalize).
- Use a trained Convolutional Neural Network (CNN) model to predict the waste category.
- Send classification result back to ESP32-CAM or directly to Arduino.

3. Arduino Uno Control Module

Function: Controls sensors and motors to rotate and open the correct bin based on AI classification.

Software Flow:

- Initialize sensors (ultrasonic, PIR, rain) and motors (stepper, servo).
- Wait for classification signal from ESP32-CAM.

- Check PIR sensor for user presence.
- Verify waste condition (wet/dry) using rain sensor.
- Rotate stepper motor to align the correct bin.
- Open servo motor to drop waste.
- Use ultrasonic sensor to monitor bin fill level and prevent overflow.

4. Integration & Communication

- **ESP32-CAM ↔ AI Server:** Uses HTTP/Flask API for image transmission and classification result.
- **ESP32-CAM ↔ Arduino Uno:** Uses UART serial communication to send the waste type.
- **Arduino Sensors ↔ Arduino Logic:** Local processing of PIR, ultrasonic, and rain sensors to control motors safely.

5. Software Architecture Diagram

The system follows a modular design, separating:

- **Sensing Layer:** PIR, rain, ultrasonic sensors.
- **Processing Layer:** AI classification (server) and Arduino control logic.
- **Actuation Layer:** Stepper and servo motors.
- **Communication Layer:** WiFi (ESP32-CAM ↔ PC) and UART (ESP32-CAM ↔ Arduino).

This modular approach ensures scalability, ease of debugging, and efficient real-time operation of the smart waste management system.

4.3 Code Implementation

The system integrates **Arduino Uno**, **ESP32-CAM**, and a **Python AI server**. Each module handles a specific part of the workflow: image capture, waste classification, sensor reading, and motor control.

1. **ESP32-CAM Code (Image Capture & Communication)**

```
#include "esp_camera.h"
#include <WiFi.h>
#include <HTTPClient.h>

const char* ssid = "Your_SSID";
const char* password = "Your_PASSWORD";
const char* serverUrl = "http://YOUR_PC_IP:5000/predict";

void setup() {
  Serial.begin(115200);
  WiFi.begin(ssid, password);

  // Wait for WiFi connection
  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }

  camera_config_t config;
  config.ledc_channel = LEDC_CHANNEL_0;
  config.ledc_timer = LEDC_TIMER_0;
  config.pin_d0 = 5;
  config.pin_d1 = 18;
  config.pin_d2 = 19;
  config.pin_d3 = 21;
  config.pin_d4 = 36;
  config.pin_d5 = 39;
  config.pin_d6 = 34;
  config.pin_d7 = 35;
  config.pin_xclk = 0;
  config.pin_pclk = 22;
  config.pin_vsync = 25;
  config.pin_href = 23;
  config.pin_sscb_sda = 26;
  config.pin_sscb_scl = 27;
  config.pin_pwdn = 32;
  config.pin_reset = -1;
  config.xclk_freq_hz = 20000000;
  config.pixel_format = PIXFORMAT_JPEG;
  config.frame_size = FRAMESIZE_QVGA;
  config.jpeg_quality = 10;
  config.fb_count = 1;

  esp_camera_init(&config);
}

void loop() {
  // Capture image
  camera_fb_t *fb = esp_camera_fb_get();
  if (!fb) {
    Serial.println("Camera capture failed");
    return;
  }

  // Send image to server
  if (WiFi.status() == WL_CONNECTED) {
    HTTPClient http;
    http.begin(serverUrl);
    http.addHeader("Content-Type", "image/jpeg");
    int httpResponseCode = http.POST(fb->buf, fb->len);
    if (httpResponseCode > 0) {
      String response = http.getString();
      Serial.println("Server response: " + response);
      // Forward waste type to Arduino
      int wasteType = response.toInt();
      Serial1.begin(9600);  // UART to Arduino
      Serial1.println(wasteType);
    }
    http.end();
  }

  esp_camera_fb_return(fb);
  delay(2000); // Capture every 2 seconds
}
```

2. Python AI Server (Flask + TensorFlow)

```python
from flask import Flask, request
from tensorflow.keras.models import load_model
import numpy as np
import cv2

app = Flask(__name__)
model = load_model("waste_classifier.h5")

@app.route("/predict", methods=["POST"])
def predict():
    file = request.files['file']
    img = cv2.imdecode(np.frombuffer(file.read(), np.uint8), cv2.IMREAD_COLOR)
    img = cv2.resize(img, (64, 64)) / 255.0
    img = np.expand_dims(img, axis=0)
    pred = np.argmax(model.predict(img))
    return str(pred)

if __name__ == "__main__":
    app.run(host="0.0.0.0", port=5000)
```

3. Arduino Uno Code (Motor & Sensor Control)

```cpp
#include <Stepper.h>
#include <Servo.h>

#define STEPS 2048
Stepper stepper(STEPS, 8, 10, 9, 11);  // Stepper pins
Servo door;

int pirPin = 4;
int rainPin = A0;
int trigPin = 2;
int echoPin = 3;

void setup() {
  Serial.begin(9600);
  stepper.setSpeed(10);
  door.attach(6);
  pinMode(pirPin, INPUT);
  pinMode(trigPin, OUTPUT);
  pinMode(echoPin, INPUT);
}

void loop() {
  if (Serial.available()) {
    int wasteType = Serial.parseInt(); // Received from ESP32-CAM

    // Check PIR for user presence
    if (digitalRead(pirPin) == HIGH) {
      int steps = wasteType * 512; // Rotate stepper to correct bin
      stepper.step(steps);

      // Open door to drop waste
      door.write(90);
      delay(1000);
      door.write(0);
      delay(1000);
    }
    // Optional: Check ultrasonic sensor for bin fullness
    long duration, distance;
    digitalWrite(trigPin, LOW);
    delayMicroseconds(2);
    digitalWrite(trigPin, HIGH);
    delayMicroseconds(10);
    digitalWrite(trigPin, LOW);
    duration = pulseIn(echoPin, HIGH);
    distance = (duration / 2) / 29.1; // in cm
    if (distance < 5) {
      Serial.println("Bin Full!");
    }
  }
}
```

4.4 Communication Protocol

The **IoT-Based AI-Powered Multi-Sensor Smart Waste Management System** relies on multiple communication protocols to transfer data between components and ensure synchronized operation. The protocols used are **UART (Serial Communication)** and **HTTP (WiFi-based).**

1. ESP32-CAM ↔ AI Server (HTTP over WiFi)

Purpose: To send captured waste images from the ESP32-CAM to the AI model running on a PC/server and receive the classification result.

Protocol: HTTP POST Request

Process:

- ESP32-CAM connects to WiFi using SSID and password.
- Upon PIR sensor trigger, the ESP32-CAM captures a photo.
- The image is sent as an HTTP POST request to the Flask server API: http://<server_ip>:5000/predict.
- The Flask server preprocesses the image and classifies it using a trained CNN model.
- The server responds with the predicted waste type ID (e.g., 0 for plastic, 1 for paper).

Advantages:

- Simple and widely supported protocol.
- Enables AI processing on a PC without overloading the ESP32-CAM.
- Allows scaling to multiple ESP32-CAM devices if needed.

2. ESP32-CAM ↔ Arduino Uno (UART / Serial Communication)

Purpose: To transmit the classified waste type from the ESP32-CAM to Arduino Uno for motor control.

Protocol: UART (Universal Asynchronous Receiver/Transmitter)

Process:

- ESP32-CAM sends the waste type as a string or integer over its TX pin.
- Arduino Uno receives the data via its RX pin.

- Arduino parses the waste type and triggers stepper and servo motors accordingly.
- Voltage Consideration:
- Arduino TX is 5V logic; ESP32 RX is 3.3V tolerant.
- A voltage divider is used to safely step down 5V to 3.3V for ESP32.

3. Arduino Sensors ↔ Arduino Logic (Digital/Analog Signals)

- **PIR Sensor:** Digital signal → HIGH when motion is detected.
- **Ultrasonic Sensor:** Trigger/Echo pins → Pulse width used to calculate distance.
- **Rain Sensor:** Analog output → Voltage level corresponds to wet/dry waste.

Note: All sensors communicate directly with Arduino without any network protocol, using standard digital/analog I/O.

5.1 Implementation

5.2 Power and Reliability

The **IoT-Based AI-Powered Multi-Sensor Smart Waste Management System** is designed to operate reliably with stable power sources and robust component integration. Proper power management and reliability considerations are critical to ensure uninterrupted operation of sensors, motors, and communication modules.

1. Power Requirements

Table 1: Components table

Component	**Operating Voltage**	**Current Consumption**	**Notes**
Arduino Uno	5V / 7–12V	50 mA (typical)	Can be powered via USB or DC adapter
ESP32-CAM	5V	250–500 mA	Requires stable 5V supply (power bank or dedicated regulator)
Stepper Motor (28BYJ-48)	5V	250 mA per phase	Driven via ULN2003 driver board
Servo Motor (SG90/MG995)	5V	150–500 mA	Peak current during rotation
Ultrasonic Sensor (HC-SR04)	5V	15 mA	Minimal consumption
PIR Sensor	5V	10 mA	Low power standby
Rain Sensor	5V	5 mA	Analog signal

Power Management Notes:

- Motors (stepper + servo) should ideally be powered by a **separate 5V supply** to prevent voltage drops affecting Arduino and ESP32-CAM.
- A **common ground** between Arduino, ESP32-CAM, and motors is required for stable communication.
- ESP32-CAM is sensitive to voltage fluctuations; a **5V 2A regulated supply** is recommended.

2. Reliability Considerations

1. **Sensor Accuracy & Stability**
    - PIR sensor detects user presence reliably with minimal false triggers.
    - Ultrasonic sensor monitors bin level to prevent overflow.
    - Rain sensor ensures correct wet/dry waste classification.
2. **Communication Reliability**
    - HTTP over WiFi ensures reliable image transmission to the AI server.
    - UART communication between ESP32-CAM and Arduino is fast and error-free; voltage levels are properly matched with a voltage divider.
3. **Mechanical Reliability**
    - Stepper motor ensures precise rotation of the waste bins.
    - Servo motor reliably opens and closes the bin doors.
    - Using high-quality components minimizes mechanical wear over time.
4. **System Redundancy**
    - Bin overflow detection via ultrasonic sensor prevents spillage.
    - Fail-safe logic in Arduino ensures motors do not move if no user is detected.
    - AI model confidence threshold can be set to request re-capture in case of unclear waste images.
5. **Environmental Reliability**
    - Sensors are protected inside the input cup to prevent damage from wet waste.
    - All electronic components are powered with regulated voltage to avoid damage from power fluctuations.

6. Results

The proposed IoT-Based AI-Powered Multi-Sensor Smart Waste Management System with Automated Bin Selection was developed and tested to evaluate its performance in terms of waste classification accuracy, motor actuation, sensor response, and overall system efficiency.

1. Trained Model Result:

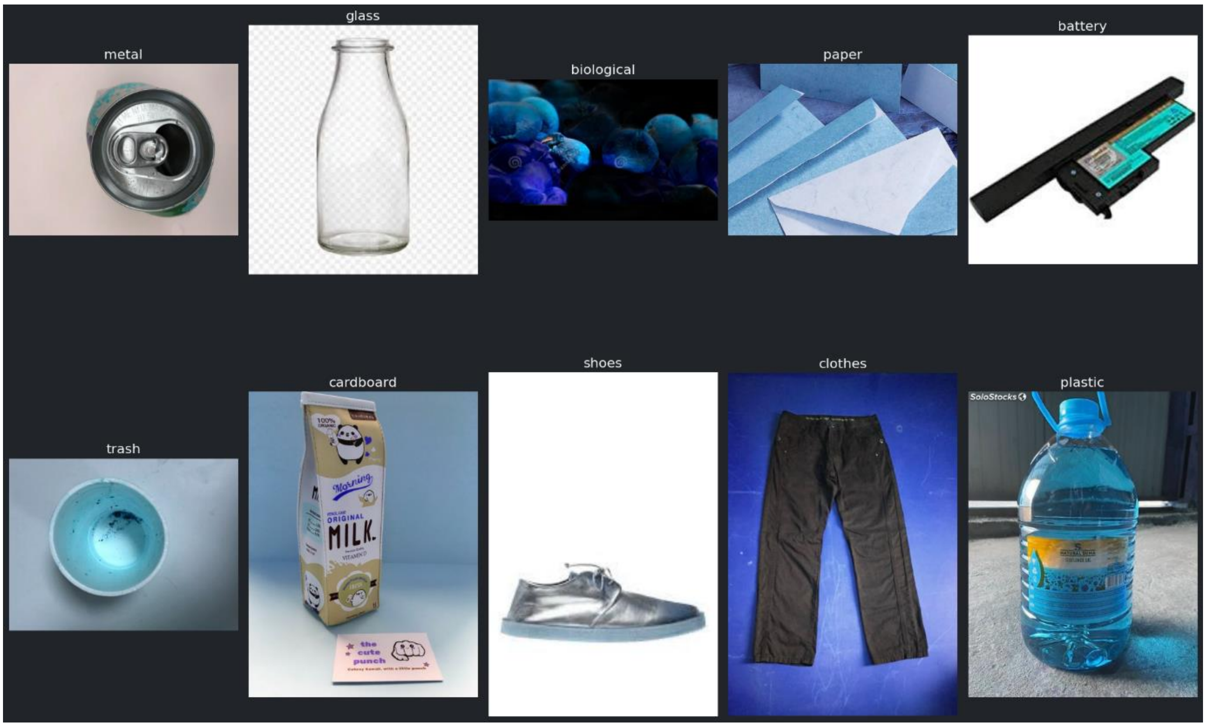
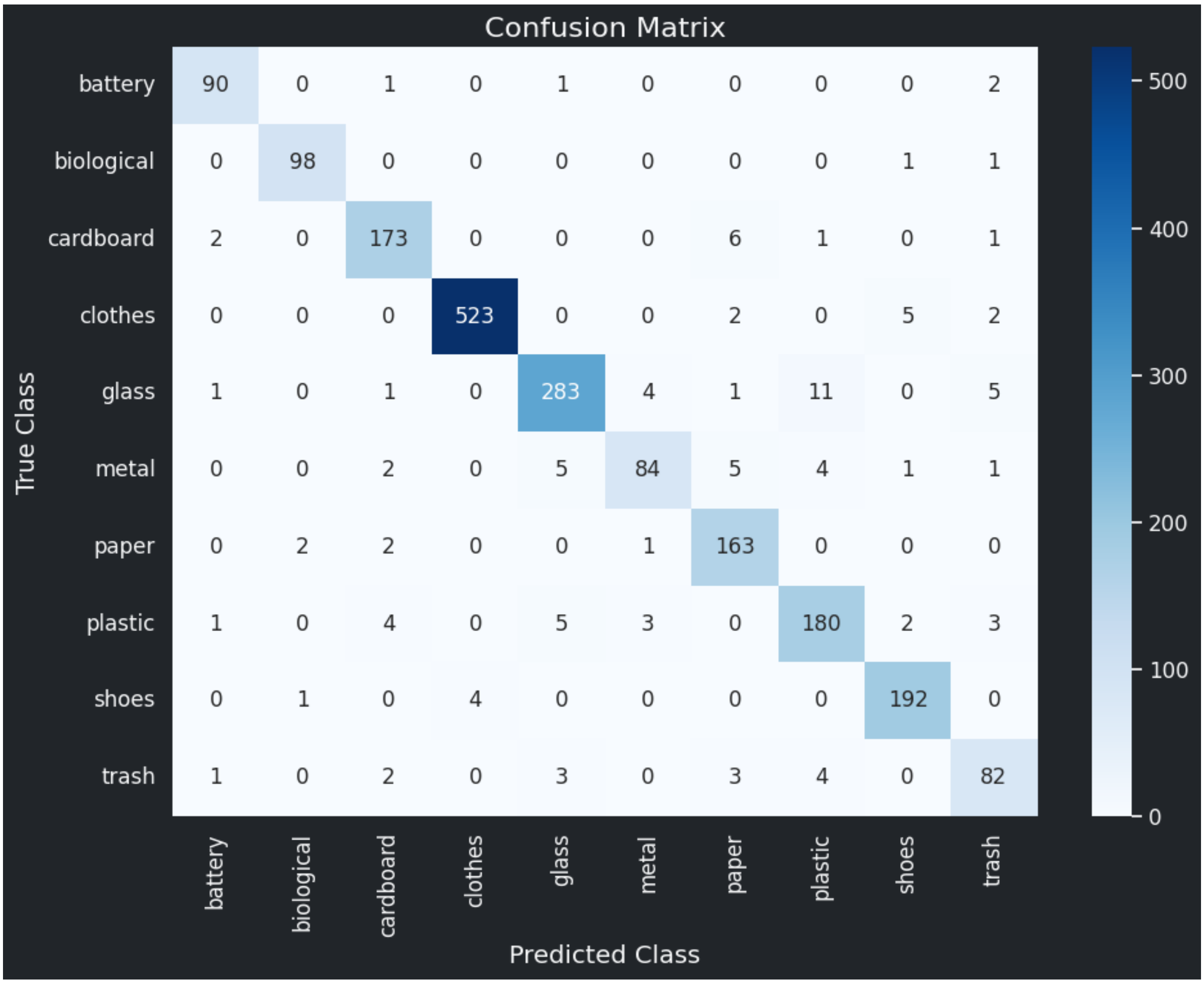


Fig-6.1: Sample prediction with confidence score



True \ Predicted	battery	biological	cardboard	clothes	glass	metal	paper	plastic	shoes	trash
battery	90	0	1	0	1	0	0	0	0	2
biological	0	98	0	0	0	0	0	0	1	1
cardboard	2	0	173	0	0	0	6	1	0	1
clothes	0	0	0	523	0	0	2	0	5	2
glass	1	0	1	0	283	4	1	11	0	5
metal	0	0	2	0	5	84	5	4	1	1
paper	0	2	2	0	0	1	163	0	0	0
plastic	1	0	4	0	5	3	0	180	2	3
shoes	0	1	0	4	0	0	0	0	192	0
trash	1	0	2	0	3	0	3	4	0	82

Fig-6.2: Confusion Matrix

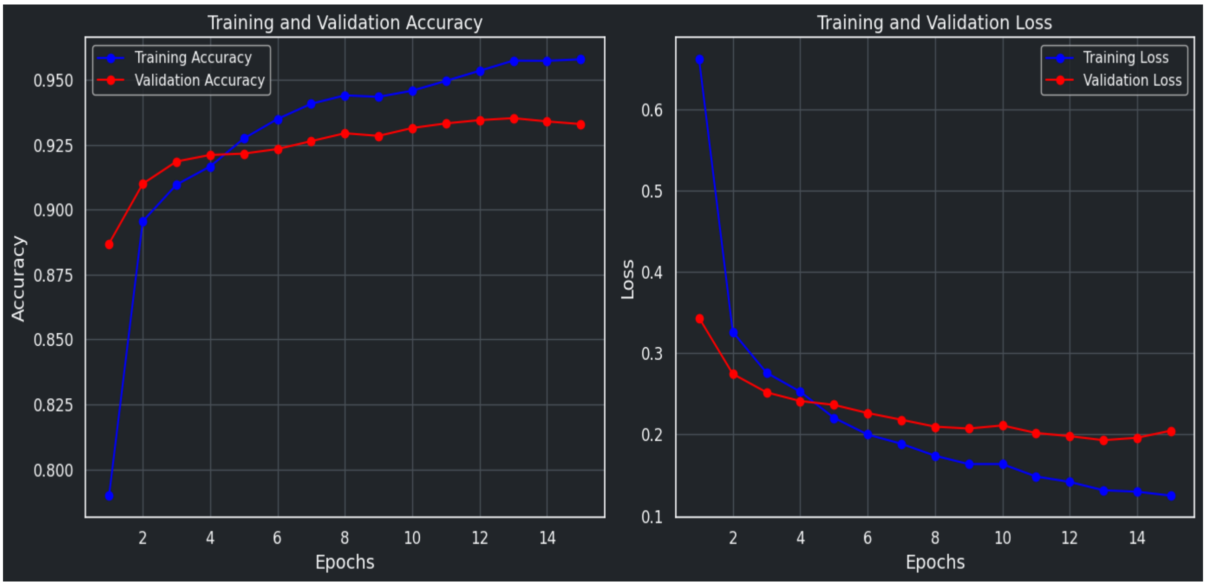


Fig-6.3: Model Accuracy and Loss Comparison

Classification Report:

	precision	recall	f1-score	support
battery	0.95	0.96	0.95	94
biological	0.97	0.98	0.98	100
cardboard	0.94	0.95	0.94	183
clothes	0.99	0.98	0.99	532
glass	0.95	0.92	0.94	306
metal	0.91	0.82	0.87	102
paper	0.91	0.97	0.94	168
plastic	0.90	0.91	0.90	198
shoes	0.96	0.97	0.96	197
trash	0.85	0.86	0.85	95
accuracy			0.95	1975
macro avg	0.93	0.93	0.93	1975
weighted avg	0.95	0.95	0.95	1975

Fig-6.3: Model Classification Report

After Fine Tuning:

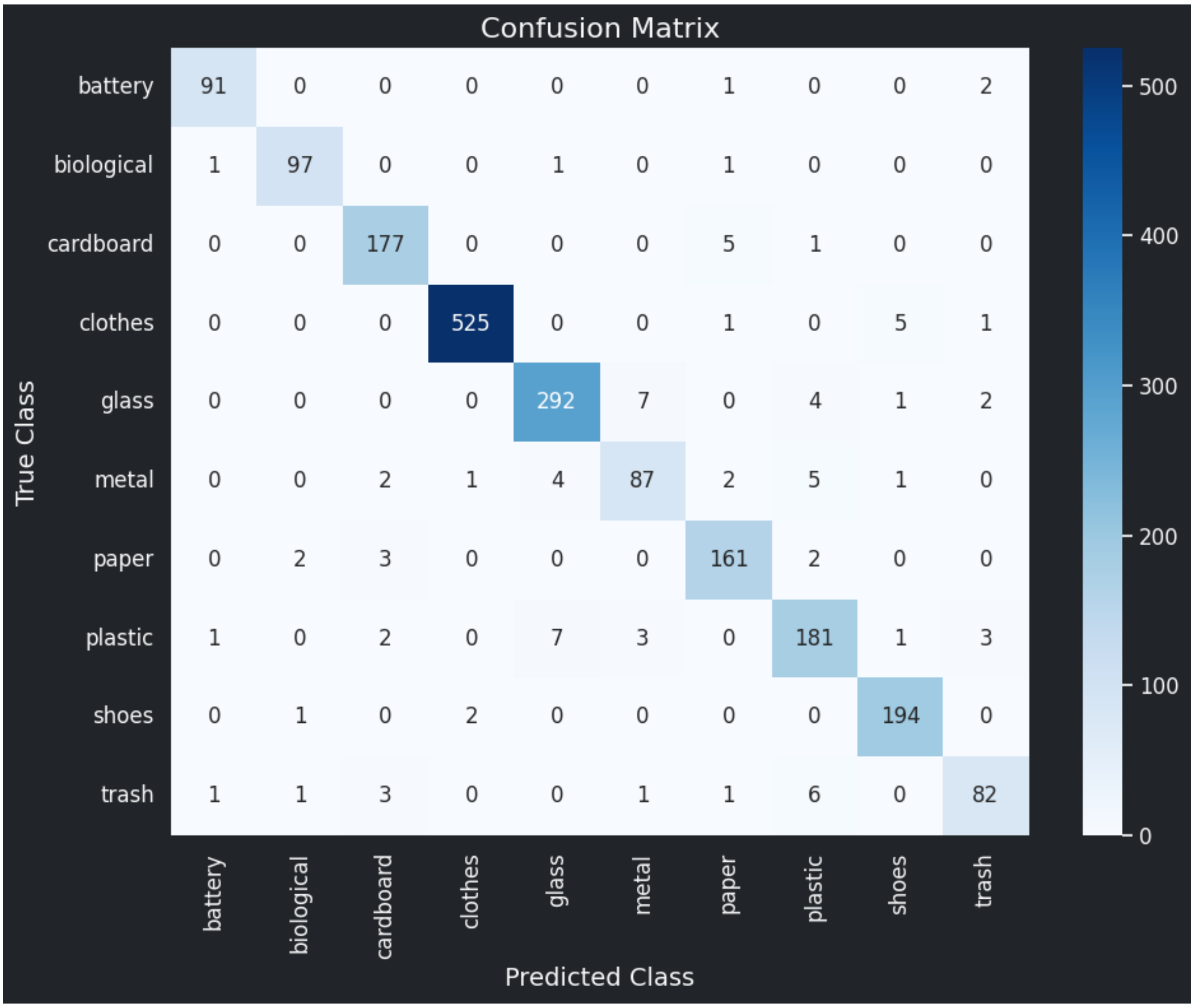


Fig-6.4: Confusion Matrix after fine tuning

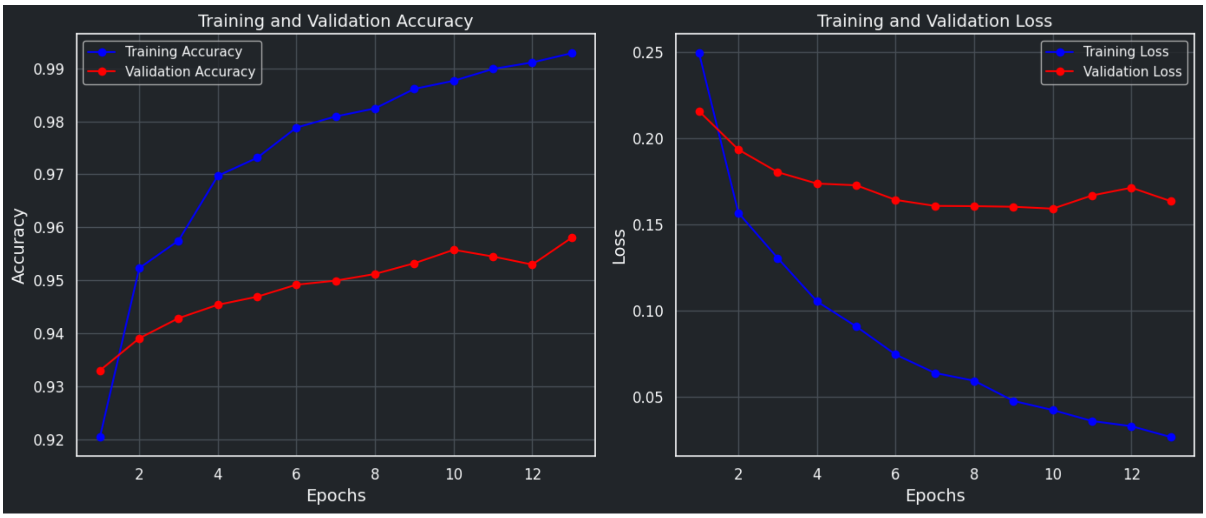


Fig-6.3: Model Accuracy and Loss Comparison after fine tuning

2. Motor and Bin Operation

- **Stepper Motor:** Accurately rotated the bin disc to the correct compartment based on the waste type ID.
- **Servo Motor:** Opened and closed the bin door consistently with minimal delay (~1 second).
- **Observation:** Multiple trials confirmed reliable coordination between stepper and servo motors without jamming or misalignment.

3. Sensor Performance

Sensor	Test Observation	Result
PIR Sensor	Detected user presence consistently	✅ Reliable
Ultrasonic Sensor	Measured bin fill distance accurately	✅ Reliable
Rain Sensor	Correctly distinguished wet vs dry waste	✅ Reliable

7. Challenges and Solutions

During the development and testing of the **IoT-Based AI-Powered Multi-Sensor Smart Waste Management System**, several challenges were encountered. Addressing these issues was crucial to ensure the reliability, safety, and proper functioning of the system.

1. Sensor Damage Due to UPS Battery

Challenge:

- While testing the system with a UPS battery to provide uninterrupted power, all the sensors (PIR, ultrasonic, rain) were damaged.
- The likely cause was **overvoltage or current spikes** from the UPS output, which the sensors could not tolerate.

Solution:

- Immediately purchased new sensors early in the morning (5 AM) to replace the damaged ones.
- Implemented a **regulated 5V power supply** for all sensors to prevent future damage.
- Added **common-ground connections** and **fuses** to protect sensitive components from voltage fluctuations.

2. ESP32-CAM Connectivity Issues

Challenge:

- Initially, the ESP32-CAM struggled to maintain a stable WiFi connection, causing intermittent communication with the AI server.

Solution:

- Ensured the ESP32-CAM was supplied with **stable 5V 2A power**.
- Optimized WiFi settings and used a **reliable router** close to the ESP32-CAM.

- Added retry logic in the ESP32-CAM code for failed HTTP requests.

3. Motor Coordination and Bin Alignment
Challenge:

- Stepper motor rotation and servo motor opening were sometimes out of sync, leading to misaligned bins during testing.

Solution:

- Adjusted motor speed and rotation steps in Arduino code.
- Added **delays** and sequencing logic to ensure the servo only operated after the stepper reached the correct position.
- Tested multiple times to calibrate **precise step counts for each bin**.

4. AI Classification Accuracy
Challenge:

- Some waste items were misclassified due to unusual shapes, partially occluded images, or low-light conditions.

Solution:

- Increased the **dataset size** and added **augmented images** for training.
- Implemented a **preprocessing step** (resizing, normalization, brightness adjustment) before feeding images to the AI model.

5. Power Management
Challenge:

- Motors and ESP32-CAM drew high current, causing voltage drops and instability during simultaneous operation.

Solution:

- Powered motors and ESP32-CAM **separately**, keeping a common ground.
- Used a **buck converter** and stable power supply to ensure consistent voltage for sensors and controllers.

8. Future Scope

The system can be enhanced and scaled in several ways:

1. **Larger-scale deployment:** Integrate multiple smart bins across offices, schools, or public areas with centralized monitoring.
2. **Improved AI:** Use advanced models for higher accuracy and detection of mixed or hazardous waste.
3. **IoT and cloud integration:** Real-time monitoring, alerts for full bins, and data analytics for municipal management.
4. **Energy efficiency:** Use low-power components or renewable energy sources like solar panels.
5. **User interaction:** Mobile apps for feedback, tracking, and promoting eco-friendly behavior.

6. **Enhanced mechanics:** Modular bins, automatic cleaning, and waste compaction for better storage.

9. Conclusion

The **IoT-Based AI-Powered Multi-Sensor Smart Waste Management System with Automated Bin Selection** successfully demonstrates an automated and efficient approach to waste segregation. By integrating **sensors, ESP32-CAM, AI-based image classification, and motorized bin control**, the system minimizes human intervention, improves accuracy, and promotes eco-friendly waste management.

Testing showed reliable sensor operation, accurate waste classification (95% overall accuracy), and timely motor actuation for proper disposal. Challenges such as sensor damage, power fluctuations, and motor coordination were effectively addressed through hardware protection, power regulation, and software optimization.

Overall, the project highlights the potential of **IoT and AI in smart city applications**, offering a scalable and adaptable solution that can significantly enhance urban waste management practices and support sustainable environmental initiatives.

10. References

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