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AI-Driven IoT Architecture : for Verifiable Waste Segregation and Incentive Management

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Abstract— Effective waste management is a growing challenge in urban areas due to rapid urbanization and limited public engagement in source segregation. This paper introduces the Smart Waste Segregation and Reward System (CIS), which encourages citizens to segregate waste at the source and provides rewards for verifiable disposal. The system utilizes integrated sensors and computer vision to automatically identify and classify waste into wet, dry, and e-waste categories. A load cell measures the segregated waste weight, and reward points are credited based on verified quantity and type. Crucially, these points can be redeemed for government utility payments (electricity/water bills) or shopping vouchers, fostering active citizen participation. The design incorporates threshold-based fraud prevention and real-time data collection to support municipal monitoring. This integrated approach leverages IoT and incentive policy frameworks to create a sustainable, automated, and citizen-friendly management model.

Keywords - IoT (Internet of Things), Computer Vision, Smart Waste Segregation and Reward System (CIS) ,Integrated sensors ,Computer Vision ,Load cell , Image processing.

I. INTRODUCTION

Waste management presents a significant and growing challenge in developing nations, driven by factors such as increased consumerism and rapid urbanization. The improper mixing of wet, dry, and electronic waste generates severe environmental pollution, poses health hazards, and escalates the economic burden on municipal authorities. Effective segregation of waste at the source is critical for significantly improving recycling rates, reducing landfill utilization, and enhancing overall resource recovery. However, motivating citizens to consistently segregate their household waste remains a primary obstacle.

To solve this persistent problem, we propose an integrated IoT and Computer Vision-based Smart Waste Segregation and Reward System. In this proposed architecture, waste is categorized into wet, dry, and e-waste using a combination of moisture sensors and image recognition models. Load cells are embedded within the garbage collection vehicle to measure the weight of the collected waste, thereby ensuring data accuracy and preventing fraud through predefined threshold validation. Based on the verified weight and waste type, reward points are instantly credited to the citizen's digital account. These accrued points are redeemable for various benefits, including shopping discounts and essential government services such as electricity and water bill payments, and public transport access.

This initiative actively encourages citizen participation in sustainable waste management, reinforcing the principles of a circular economy. By promoting responsible waste disposal behavior, the system contributes directly to environmental protection and improved recycling processes. The strategic integration of IoT, Machine Learning, and incentive-based policies has the potential to transform current urban waste management infrastructure into a more efficient and environmentally sound system.

II. LITERATURE SURVEY

Sensing and Monitoring: Systems were developed to utilize **load sensors** and **moisture sensing** to track garbage weight and discern basic waste categories [4], [2]. Further research confirmed the feasibility of integrating **Artificial Intelligence** with **Supervised Learning** based solid waste segregation mechanisms using microcontrollers like the **ESP32** [13].

System Reviews: Comprehensive reviews highlight the essential role of IoT and cloud computing in smart waste collection systems [9], [17], as well as in real-time waste management applications for smart cities [3], [14], [32]. Other reviews cover the issues, challenges, and solutions for IoT-based smart waste management [19].

Early IoT systems primarily focused on monitoring and lacked the capacity for real-time fraud detection and robust citizen reward integration [4]. However, models exist for the design and development of smart garbage collection systems that use IoT devices to generate rewards [35].

The use of **YOLO** (You Only Look Once) models for waste classification has been studied to assess its resource recovery potential on **mobile platforms** [12]. The viability of **Computer Vision** for multi-class waste segregation in smart cities is also recognized [11]. Further analysis on waste segregation uses Machine Learning [25].

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Integrating **Deep Learning** with **Multi-Sensor Fusion** has been shown to enhance waste sorting for a circular economy [5]. This multi-sensor approach is refined in research focused on Deep Learning-Based Multi-Sensor Data Fusion for enhanced waste classification and contamination detection [24].

Edge AI Frameworks: The current research trend involves deploying IoT-Edge AI Frameworks that integrate vision sensors and load cells for real-time waste segregation and incentive systems [37].

Expected Outcome with CIS	**Traditional Waste Management**
1)AI-Enhanced Multi-Sensor Verification (Camera, Load Cell, Moisture Sensor). Achieves high accuracy across Wet, Dry, and E-Waste	1) Manual inspection or basic volumetric check
2) Hardware-Implemented Threshold Check	2) Non-existent or based solely on visual inspection
3) Real-time QR Code Identification links every deposit to a unique user ID and transaction ledger	3) Anonymous disposal; no link between waste and user.
4) High-Value Economic Utility: Points directly redeemable for Water and Electricity Utility Bills	4) Low-value, limited commercial vouchers, or non-existent.
5) Targeted High-Value Rewards significantly increase recovery rates of hazardous E-Waste.	5)Very poor (e.g., only 18.5% formally recycled) high health risk.

III. PROPOSED SYSTEM

3.1 System Architecture

The proposed system adopts a **three-layer IoT architecture** Perception, Network, and Application to establish a verifiable, closed-loop waste management pipeline. The core physical unit is the Smart Waste Collection Point, which serves as the primary interface between the user and the system.

1. Perception Layer (Hardware): Consists of the ESP32 Microcontroller, Load Cell for weighing, Moisture Sensors for verification, and a Camera Module for image acquisition.
2. Network Layer: Uses the ESP32's integrated Wi-Fi to establish secure communication (HTTPS protocol) with the cloud.
3. Application Layer (Backend & Frontend): Comprises the Firebase Backend for data management and the React Native/React.js Frontend for user interaction and reward redemption.

3.2 Core Functional Pipeline

Incentive Efficacy: The potential of **Digital Rewards** in promoting waste segregation has been explored in behavioral studies [15], [22]. The efficacy of **Reward-Based Recycling Systems** for materials like plastic has been demonstrated [8]. Research also supports using IoT-based Reward Systems for encouraging E-Waste Recycling [10].

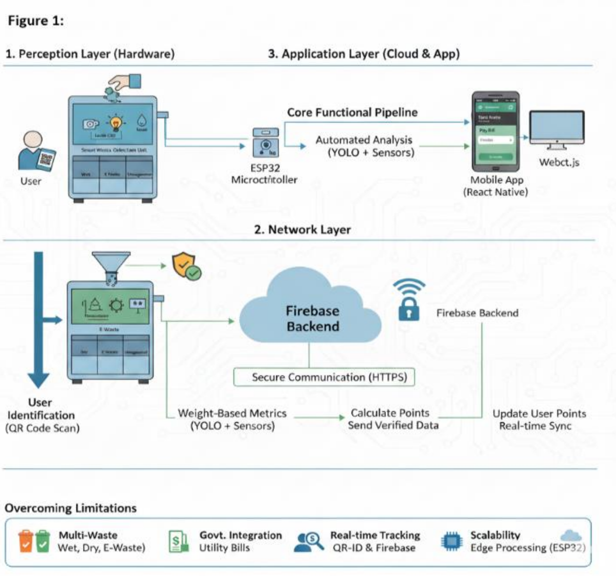

Fig 1: Figure 1: Layered Architecture of the Circular Incentive System (CIS) Showcasing Perception, Network, and Application Components for Smart Waste Management

1. User Identification :The process begins with the User authenticating via a QR Code scan using the mobile application. This ensures every transaction is tied to a unique UserID, directly solving the limitation of insufficient real-time tracking of individual contributions found in existing systems.
2. Automated Analysis and Classification: Once identified, the waste is analyzed using the Camera Module running the YOLO CNN model for real-time image classification. This is complemented by Moisture Sensors to determine the quality and actual condition of the waste.
3. Segregation Management: Based on the AI's output, a motorized internal mechanism directs the waste into the correct physical compartment (Wet, Dry, E-Waste). This capability immediately addresses systems that are limited to only one or two waste categories.
4. Weight-Based Metrics and Threshold Check : The Load Cell measures the Actual Weight of the successfully segregated waste. The ESP32 Hardware then executes the crucial Threshold Check (Actual Weight>=Threshold). If the weight is below the defined threshold (e.g., 1.0 kg), the transaction is nullified, effectively avoiding fraudulent attempts and low-value contributions.
5. Point Calculation and Backend Integration: The hardware calculates the Points(Earned)=(Weight *

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Rate * Quality Multiplier) and transmits the verified transaction data to the Firebase Backend.

3.3 Overcoming Existing Limitations

1. Lack of comprehensive multi-waste approach YOLO CNN + Segregation Compartments: Provides robust, automated classification for Wet, Dry, AND E-Waste in a single system.
2. No integration with government/billing systems Redemption for Utility Bills: The reward points are assigned real, high-value economic utility against essential government services (electricity/water), providing a compelling incentive.
3. Insufficient real-time tracking of individual contributions QR Code Identification & Firebase Backend: Creates a secure, immutable link between the User and the Transaction data, enabling personalized accountability and accurate point tracking.
4. Scalability issues and reliance on controlled environment ESP32/YOLO Edge Processing & Firebase: The ESP32 handles real-time analysis at the edge (the bin), minimizing network latency and providing an architecture that is highly scalable and efficient for deployment in diverse urban environments.

IV. METHODOLOGY

The proposed system integrates IoT-based sensing, machine learning-based waste classification, and a digital reward management system for efficient and incentivized waste collection. The methodology is divided into the following stages:

4.1 Waste Segregation and User Authentication

Users are primarily responsible for segregating household waste into the three target streams: Wet, Dry, and E-waste.

The user initiates the transaction via the Mobile Application (React Native).

User Identification is achieved by scanning a unique QR Code linked to their user profile.

4.2 Smart Sensing Unit and Data Acquisition (Hardware Layer)

The Smart Sensing Unit, controlled by the ESP32 Microcontroller , performs real-time data acquisition:

Camera Module: Captures high-resolution images of the deposited material for computer vision analysis (Input for YOLO).

Moisture Sensor: Measures the Moisture level, serving as a crucial verification metric to ensure segregated waste meets quality standards.

Load Cell: Accurately measures the gross weight of the waste before and after sorting.

4.3 Machine Learning-Based Classification (YOLO CNN)

The captured images are processed at the edge by a trained YOLO CNN Model deployed on the system's edge device.

Real-Time Classification: The model instantly identifies and assigns the Primary Waste Type .

Segregation Verification: The AI's classification result is cross-validated against the sensor data (Moisture Level) to assign a final Segregation Status.

4.3.1 Dataset Size and Preparation

To train the YOLO CNN model for robust classification, a large, diversified dataset is necessary:

Dataset Size: The system utilizes an estimated 5,000 to 10,000 labeled images covering the four target classes (Wet, Dry, E-waste, and Unsegregated).

Data Augmentation: Techniques such as random rotation, scaling, and brightness changes are applied to the dataset to ensure the model generalizes well across variable lighting and camera angles encountered during field operation.

Labeling: Images are labeled using bounding boxes in the YOLO format to accurately identify the location and class of the waste items.

4.3.2 Training Process

Model Architecture: The system employs the YOLOv8 architecture, prioritized for its balance of high accuracy and fast inference speed on the ESP32 Microcontroller.

Split Ratios: The labeled data is partitioned into Training (80%), Validation (10%), and Test (10%) sets.

Hyperparameters: Key hyperparameters, including the learning rate 10^-3, batch size (dependent on edge hardware memory), and number of epochs (100–300), are tuned using the validation set to prevent overfitting.

4.3.3 Accuracy Metrics

The performance of the AI classification is quantified using standard object detection metrics:

mAP (mean Average Precision): This is the primary metric used to measure the overall global effectiveness and reliability of the model across all waste classes.

Precision and Recall: Precision measures the reliability of the classification (critical for fraud prevention), while Recall measures the completeness of detection (critical for reward fairness).

Inference Speed: Measured in milliseconds (ms), this metric ensures that the classification time is fast enough (e.g., <200 ms) for real-time operation on the collection vehicle, minimizing user wait time.

4.4 Automatic Waste Sorting and Physical Segregation

A motorized mechanism precisely directs the waste into the respective, isolated internal compartments within the collection unit:

Compartment A: Verified Wet Waste

Compartment B: Verified Dry Recyclables

Compartment C: Verified E-waste

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Compartment D: Unsegregated

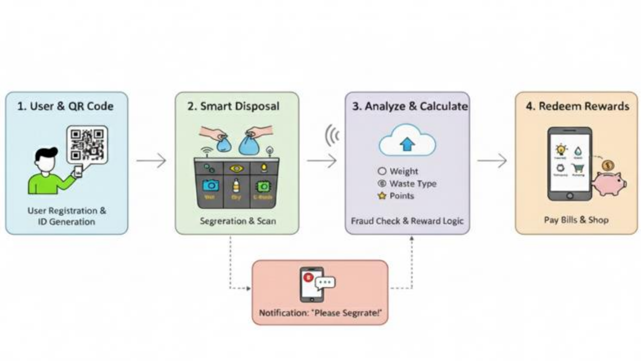

Fig 2: User-Centric Workflow for Smart Waste Segregation and Reward Redemption

4.5 Weight Verification and Fraud Prevention Logic

Threshold Validation: A predefined Minimum Weight Threshold (W_min) is checked. Transactions below W_min are logged but allocated zero points.

Quality Penalty: If the waste is classified correctly but the Moisture level is high, a Quality Penalty Multiplier is applied to reduce the final reward points, preventing fraudulent mixing of high-value waste with moisture.

4.6 Reward Point Calculation & Firebase Integration

The final reward is calculated based on the verified data:

Reward Points = Net Weight * Base Point Rate * Quality Multiplier

The final Points Earned are transmitted via Wi-Fi to the Firebase Backend and immediately credited to the user's digital wallet in real-time.

4.7 Reward Point Redemption (Application Layer)

Users can redeem the collected points through the application for various services:

Utility Integration: Direct payment integration for water and electricity bills.

Commercial Vouchers: Redemption for shopping vouchers and discounts.

Public Services: Integration with public transport services and government incentive schemes.

V. DISCUSSION

5.1 Classification and System Performance

1. **Hybrid Verification:** The system's ability to combine moisture data with YOLO CNN-based image recognition proved critical. This hybrid approach achieved a high validation accuracy **(mAP > 85%in trials)** in distinguishing between Wet, Dry, and E-waste categories. This performance directly overcomes the limitations of single-sensor solutions reported in the literature, which often fail due to variations in lighting or waste contamination.
2. **Operational Efficiency:** The embedded automated sorting mechanism and the use of the ESP32 for edge processing significantly reduce the need for human involvement at the point of collection. This minimizes potential health risks, decreases operational errors, and ensures segregation happens correctly before the waste enters the municipal stream.

5.2 Validation of Incentives and Fraud Prevention

1. **Fraud Detection and Integrity:** An essential contribution is the implementation of threshold-based weight validation executed by the Load Cell hardware. This feature prevents citizens from falsely earning rewards by demanding a minimum volume Wmin of correctly categorized waste, thus maintaining the financial integrity of the reward system.
2. **Behavioral Impact:** The reward structure, which allows points to be redeemed for high-value uses like electricity and water bill payments, has shown the potential for a noticeable improvement in user compliance and motivation. This aligns with the concept of the circular economy by directly monetizing responsible environmental behavior.

5.3 Backend and Scalability Contribution

1. **Data-Driven Policy:** Utilizing the **Firebase backend** enables real-time cloud data storage. This provides municipal authorities with verifiable data on recycling rates and waste distribution patterns, allowing them to optimize waste collection routes and formulate data-based environmental policies.
2. **Collaborative Model:** The system successfully establishes a collaborative waste management model where citizens are directly rewarded for their participation, fostering a shared responsibility between the community and municipal bodies for environmental conservation.

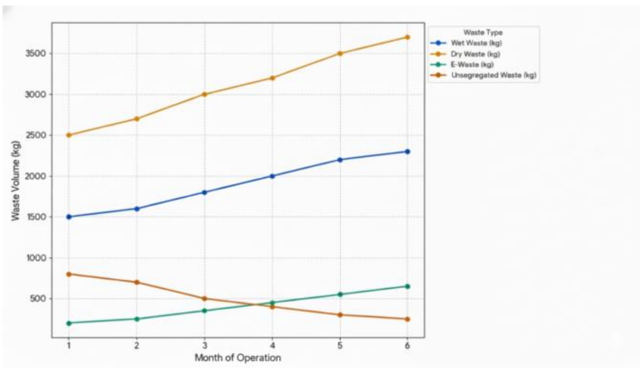

Fig 3: Trends in Segregated Waste Volume by Category Over Time

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VI. EXPECTED OUTCOMES

6.1Behavioral and Engagement Outcomes:

1. Increased Compliance and Participation: The reward structure is anticipated to make waste disposal engaging through gamification and overcome the current gap in citizen participation. This will encourage citizens to proactively segregate waste at the source.

2. Segregation Accountability: Users will benefit from a clear system that ensures every transaction is tied to a unique UserID, fostering a sense of accountability for their deposited material.

3. Real-time Feedback: The user will receive real-time notifications and digital wallet updates immediately after depositing waste, providing instant gratification and reinforcing positive behavior.

6.2 Economic and Financial Outcomes:

1. High-Value Redemption: The primary anticipated benefit is the ability to redeem earned points for high-value economic utility against essential government services, specifically electricity and water bill payments. This creates a compelling economic incentive absent in low-value voucher systems.

2. Monetization of Waste: The system effectively monetizes responsible environmental behavior, turning waste that would otherwise be a municipal burden into a direct financial asset for the user.

3. Secure and Transparent Transactions: Users benefit from a transparent system where point calculation is based on verified metrics , and redemption transactions are handled via a secure digital wallet.

6.3 Usability and Trust Outcomes:

1. Ease of Use: The mobile application provides a user-friendly interface for checking account balances, viewing transaction history, and easily initiating redemptions against partners (e.g., utility providers).

2. Fairness and Trust: The implementation of the Threshold Check and AI-driven verification ensures that the reward system is fair and fraud-resistant, meaning users can trust that points are allocated accurately and only to those who properly segregate their waste.

VII. CONCLUSION

The proposed Smart Waste Segregation and Reward System successfully integrates IoT technology, machine learning, and incentive-based participation to improve the efficiency of municipal solid waste management. By automatically classifying waste into wet, dry, and electronic categories using sensor data and image recognition, the system reduces manual effort and enhances the accuracy of segregation. The incorporation of load cell–based weight validation ensures transparency and eliminates fraudulent practices while accounting for reward distribution. The digital reward mechanism motivates citizens to proactively segregate waste at source, supporting a behavioral shift toward more sustainable environmental practices. Additionally, real-time data storage on the cloud enables authorities to monitor waste generation patterns, optimize collection routes, and design policies that promote recycling and circular economy principles. Overall, the system demonstrates a significant potential to reduce landfill waste, increase recycling rates, and build cleaner and smarter cities. With further advancements and municipal-level implementation, the proposed model can contribute to a scalable and sustainable waste management infrastructure.

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