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Research Article

IoT-Based Deep Learning Model for Sustainable Waste Management System

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ABSTRACT

India faces significant challenges in waste management due to rapid urbanization, leading to health hazards and environmental degradation. In this research, we provide an IoT-driven, deep learning-based solution for efficient waste collection, segregation, and disposal. Bins are installed with ultrasonic sensors and GPS at individual households and community areas. These bins continuously monitor the level of waste, and when the trash exceeds 80% of the bin's capacity, the waste is scheduled for collection. Garbage trucks transport the collected waste, with optimal routes generated using the Traveling Salesman Problem (TSP) algorithm and open street map API. The route includes the locations of bins that are ready for collection. Waste is segregated using moisture sensors to classify the waste based on its moisture content and the next level of segregation is done by using ResNet50 to classify the dry waste into subcategories like metal, cardboard, plastic, glass, and textiles for precise disposal. After segregation, the garbage is disposed into recyclable, non-recyclable, and biodegradable categories. such as incinerating non-recyclable waste to generate electricity, transferring recyclable waste to recycling facilities, and composting organic waste. The proposed solution reduces landfill dependency, increases recycling rates, and generates energy from waste. This work has potential to revolutionize waste management practices in urban and rural environments.

Keywords: IOT, ultrasonic and moisture sensors, Traveling Salesman Problem, Deep learning, Resnet-50, smart bins, open street map API, segregation Level.

1. INTRODUCTION

Waste management is a growing challenge in rapidly urbanizing regions, particularly in countries like India, where traditional systems struggle to handle the increasing waste volumes of expanding populations. These systems often face inefficiencies in waste collection, segregation, and disposal, leading to overflowing bins, improper separation, and over-reliance on landfills, which harm the environment and public health. This paper presents a comprehensive waste management solution integrating deep learning and IoT technology for real-time monitoring, precise classification, and optimized collection. Using the ResNet- 50 CNN model, waste is accurately categorized based on images, while ultrasonic sensors monitor bin levels for timely collection, and GPS enables route optimization. A moisture sensor classifies waste as dry or wet, improving material separation. This system enhances efficiency, reduces environmental impact, and minimizes public health risks.

2. RELATED WORK

Traditional waste management systems primarily rely on manual processes for waste collection and segregation, leading to inefficient operations that result in delayed collections, overflowing bins, and increased operational costs [3]. The conventional approach to waste management often neglects proper segregation, contributing to the loss of recyclable materials and excessive dependence on landfills [2]. Recent technological advances have introduced Internet of Things (IoT) based solutions for waste management. These modern systems incorporate sensors for real-time monitoring of waste levels, where IoT-enabled waste bins equipped with ultrasonic sensors measure fill levels to optimize collection routes [6]. The implementation of smart waste bins has demonstrated significant improvements in collection efficiency through real-time monitoring and data transmission capabilities.

The integration of machine learning technologies, particularly in waste classification, has emerged as a promising solution for automated waste segregation. Computer vision systems utilizing Convolutional Neural Networks (CNNs) have shown considerable potential in accurately identifying different waste materials, including plastic, metal, and organic waste [4]. However, the widespread implementation and scaling of these intelligent classification systems within existing waste management infrastructure remains a significant challenge [7]. In the context of waste processing, biogas production from organic waste has established itself as a viable solution, particularly in rural settings [8]. While waste-to-energy technologies like incineration offer potential solutions for waste reduction, they often face challenges related to emissions control and require sophisticated scrubbing systems [5]. The integration of smart waste management systems in urban environments has shown promise in improving overall waste handling efficiency and contributing to the development of smart cities [1]. The implementation of GPS-enabled tracking systems for waste collection vehicles has further enhanced route optimization and resource utilization in modern waste management systems. Recent studies have demonstrated that the interaction between waste composition and collection vehicle design significantly impacts route optimization and overall system efficiency [3]. Smart waste management solutions have proven instrumental in advancing industrial sustainability and urban development goals [5].

3. METHODOLOGY

Efficient waste management remains a critical challenge in urban areas, where overflow, improper disposal, and inefficient collection routes contribute to pollution and increased operational costs. Traditional waste collection systems often lack real-time monitoring, optimized routing, and source-level segregation, leading to fuel wastage, resource inefficiency, and environmental hazards. This paper proposes an IoT-enabled smart waste management system, integrating real-time monitoring, automated segregation, and optimized collection routes. By employing sensors, GPS, and cloud-based data management, the system aims to minimize waste overflow, improve segregation at the source, and reduce fuel consumption, ultimately promoting sustainable urban waste management.

Main Contributions of the Proposed Model:

(i)Utilize IoT-enabled smart bins equipped with ultrasonic sensors, and GPS modules for real-time waste monitoring and tracking.(ii)Encourage community participation in waste management through incentives and rewards.(iii)Implement a dual-approach collection strategy for both small-scale (household) and large-scale (community or industrial) waste management needs.(iv)Optimize transportation routes using GPS data and algorithms to prioritize nearly full bins, reducing fuel consumption and operational costs.(v)Provide an early waste pickup option to accommodate special cases and user needs.(vi)Conduct two- stage waste segregation, starting with IoT-based moisture sensors to separate wet and dry waste.(vii)Enhance recycling efficiency through deep learning-based classification using the ResNet-50 model for precise categorization of dry waste.(viii)Develop a web-based platform for community engagement, facilitate food donation, promote waste reduction campaigns.

4. IMPLEMENTATION

The proposed system leverages IoT-enabled smart bins and deep learning algorithms to automate waste management processes from collection to disposal. As depicted in architecture figure 1- the system provides a comprehensive workflow encompassing waste collection, transportation, segregation, and disposal. Designed for both household and community scales, it incorporates real-time monitoring, route optimization, and a two-stage waste segregation mechanism. Additionally, the system transforms waste into valuable resources through biogas production and recycling, while promoting community participation via a web-based incentive platform.

System Architecture

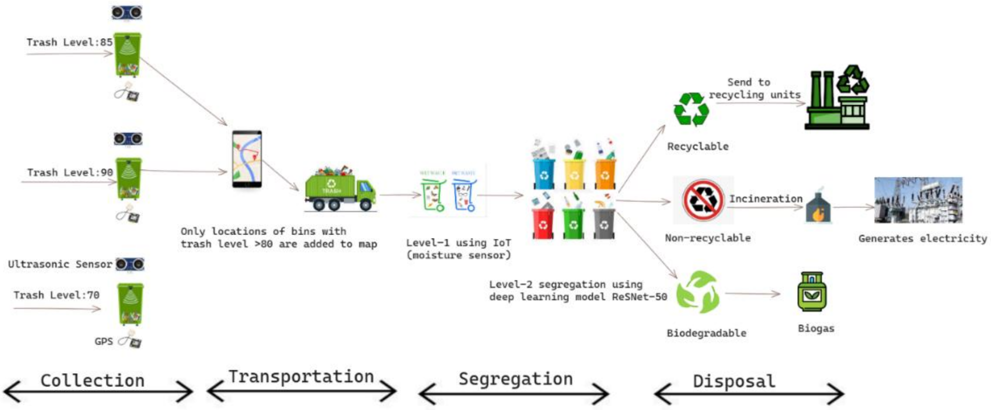

Figure 1: Architecture of the proposed method

1. Collection

IoT-enabled bins are deployed for small-scale (household) and large-scale (community or industrial) waste management. Each bin is equipped with ultrasonic sensors and Neo-6 GPS modules to monitor waste levels and track locations. The proposed solution employs a dual approach to waste collection, catering to both small-scale (household) and large-scale (community or industrial) needs. Small Scale (Households)- Small IoT bins, equipped with ultrasonic sensors, GSM, and GPS, monitor waste levels and locations. To promote usage, incentives like cash rewards and vouchers are offered, funded by a portion of collected profits. Large Scale (Community/Industry)- Large IoT bins, equipped with ultrasonic sensors, GSM, and solar panels, generate electricity for public uses (e.g., street lighting), with surplus energy sold commercially. Bins automatically close upon reaching 95% capacity, with an override option for collection personnel.

2. Transportation

When waste bins reach 80% capacity, an algorithm optimizes the collection process for efficiency. Smart Collection Routes-The system integrates GPS data from the bins to create the most efficient collection routes, prioritizing nearly full bins to minimize fuel consumption. Bins with lower waste levels are bypassed until they reach the required capacity. Handling Special Cases-An option for early pickup is available for users needing waste collection before the 80% threshold, accommodating specific circumstances like holidays.

3. Segregation

Segregating waste at the source is crucial to effective waste management. We approached this in two stages. The first stage is IoT Based Segregation using Moisture Sensor (Dry vs. Wet Waste). In this stage the waste collected is classified into dry (e.g., paper, plastic) and wet (e.g., food scraps) categories using moisture sensor based on the moisture content. The next stage of segregation is Deep Learning-Based Classification (ResNet-50). In this stage the collected waste undergoes further sorting using a ResNet-50 model, which classifies dry waste into subcategories like metal, cardboard, plastic, glass, and textiles for precise disposal. This two-level classification system ensures that waste is properly sorted and sent to the appropriate disposal process, reducing landfill usage and increasing recycling efficiency.

4. Waste Disposal

Disposal processes are specifically tailored to each waste category based on the initial classification results. For biodegradable waste, the system converts wet organic materials into biogas for energy generation, while the resulting digestate serves as fertilizer and livestock bedding. Recyclable materials, including metal, glass, and plastic, are directed to specialized recycling units for processing. Non-recyclable waste undergoes incineration for electricity generation, with wet scrubber systems deployed to neutralize toxic emissions, ensuring environmental compliance. Additionally, the project includes the development of a web- based platform to support waste management initiatives. The platform features key functionalities that enable users to donate surplus food to those in need and participate in waste reduction campaigns. To promote active community engagement, the system implements an incentive-based structure that rewards participants for their contributions to sustainable waste management practices.

Hardware Components

ESP32-Acts as the main controller, gathering sensor data, sending it to the cloud, and managing actuators. Ultrasonic Sensor-Measures bin fill level, triggers collection actions through ESP32 when waste reaches 80-95% capacity. Moisture Sensor-Differentiates between wet and dry waste, providing initial segregation for effective disposal. Stepper Motor-Automates bin lid closure at 95% capacity to prevent overflow, ensuring hygiene and containment. GPS Module (Neo-6)-Tracks bin locations, optimizing collection routes to reduce travel time, fuel, and emissions.

5. RESULTS

The results include setting up of IoT bin (Figure-2), routes generated for collecting waste (Figure-3), hardware setup for wet and dry waste segregation (Figure-4), multilevel classification results using machine learning (Figure-5) and UI interface (Figure-6).

Evaluation Metrics:

Precision: $\frac{TP}{TP+FP}$ F1 score $= \frac{2 \, X \, Precision \, X \, Recall}{Precision \, X \, Recall}$

Recall $= \frac{TP}{TP+FN}$ Accuracy $= \frac{TP+TN}{TP+FN+TN+FP}$

Figure-2: IoT Smart Bin

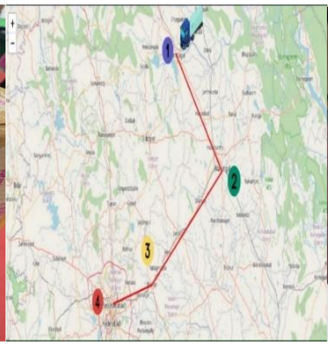

Figure-3: Generated Route

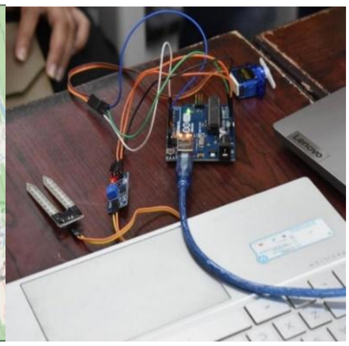

Figure-4: Hardware setup for wet and dry waste segregation

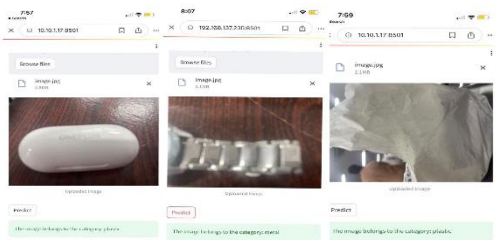

Figure-5: Results of multi-level classification using ResNet50

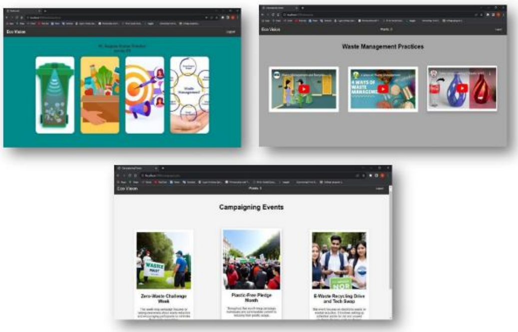

Figure-6: Results of few interfaces in the developed web

Table-1: Metrics of ML model

	Precision	Recall	F1-score
Battery	0.94	0.97	0.95

Biological	0.98	1.00	0.99
Brown-Glass	0.94	0.99	0.97
Cardboard	0.97	0.96	0.96
Clothes	0.99	0.99	0.99
Green-Glass	0.99	0.96	0.97
Metal	0.90	0.86	0.88
Paper	0.95	0.92	0.94
Plastic	0.92	0.92	0.92
Shoes	0.97	0.96	0.96
Trash	0.95	0.97	0.96
White-Glass	0.94	0.94	0.94

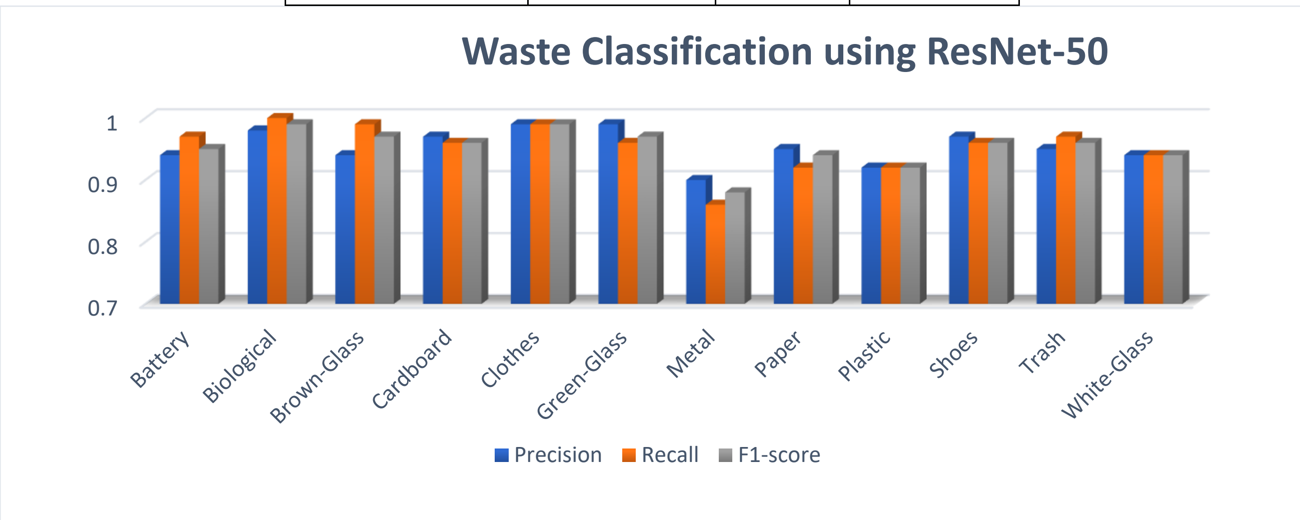

Figure 7: Performance evaluation of Waste Classification using ResNet-50 Model

6. CONCLUSION AND FUTURE SCOPE

This paper presents a novel, automated, and scalable solution to the challenges of modern waste management. Utilizing IoT technology, ResNet-50 for waste classification, and sustainable disposal methods, the system addresses inefficiencies in conventional approaches while advancing environmental and economic sustainability. It enhances waste collection through route optimization, reduces reliance on landfills, and promotes recycling, offering a practical framework for global municipal adoption. However, its dependence on cloud processing and internet connectivity may pose limitations in rural or underdeveloped regions. Future work will focus on expanding the classification model, improving biogas production, and aligning with smart city frameworks. Efforts will also refine classification accuracy and develop strategies for areas with limited infrastructure. Additionally, incentivizing smart bin usage with rewards and solar-powered electricity for communities will enhance adoption and sustainability.

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