International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

# Advancing Urban Cleanliness with Vision-Based Garbage Pickup Route Optimization Including IoT

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**ABSTRACT:**

Waste management remains one of the most pressing challenges in urban development, especially as city populations surge and solid waste generation rises. Traditional garbage collection systems, which depend on pre-scheduled, fixed routes and manual monitoring, often fall short in ensuring timely pickups, leading to overflowing bins, inefficient fuel usage, and increased operational costs. In this study, we present the design and implementation of a smart waste management solution that leverages the capabilities of computer vision, Internet of Things (IoT) technologies, and heuristic-based route optimization. The system utilizes Detectron2 for visual identification of overflowing bins, while real-time monitoring is achieved using Raspberry Pi 5 connected to ultrasonic sensors. For dynamic and optimized route planning, heuristic algorithms such as Genetic Algorithm (GA) and Ant Colony Optimization (ACO) are applied to solve the Traveling Salesman Problem (TSP). A physical prototype was developed to simulate the environment, along with a web-based dashboard that displays bin status and suggests optimized pickup routes. Upon evaluation, the system achieved a detection accuracy of 92.5%, a 100% success rate in triggering alerts when bins exceeded 80% capacity, and demonstrated a 32% reduction in fuel consumption and a 38% improvement in route efficiency compared to conventional methods. The integration of real-time data acquisition with intelligent decision-making tools makes this solution a viable and scalable model for future smart city applications in sustainable waste management.

**Keywords:** Smart waste management, Internet of Things (IoT), computer vision, Detectron2, Raspberry Pi, ultrasonic sensor, route optimization, Genetic Algorithm (GA), Ant Colony Optimization (ACO), Traveling Salesman Problem (TSP), smart cities.

## INTRODUCTION

In today's rapidly growing cities, the issue of efficient and sustainable waste collection has become increasingly critical. Municipal bodies often face significant challenges in ensuring that waste is collected on time and disposed of properly. Traditional systems rely on fixed collection routes and manual bin inspection, regardless of whether bins are full or empty. This leads to overflowing bins in some areas, underutilized pickups in others, and ultimately results in wasted fuel, increased carbon emissions, and public dissatisfaction.

The need for a more intelligent, responsive system is evident. With advances in artificial intelligence and sensor technologies, cities now have the tools to improve these services. In particular, the combination of computer vision and IoT has shown promise in automating and optimizing everyday urban processes. In the context of waste management, these technologies can provide real-time data about bin status, enable automated detection of overfilled containers, and dynamically adjust collection routes to improve efficiency.

This paper proposes a unified smart waste management system designed to overcome the limitations of existing methods. It combines three powerful components: (i) computer vision using Detectron2 for visual overflow detection, (ii) IoT-based monitoring with ultrasonic sensors and Raspberry Pi 5 for real-time fill-level tracking, and (iii) route optimization using heuristic algorithms such as Genetic Algorithm (GA) and Ant Colony Optimization (ACO) to solve the Traveling Salesman Problem (TSP).

In addition to the system design, a working prototype was built using a cardboard dustbin model, integrated with sensors, and connected to a real-time web dashboard. The dashboard visualizes bin data, triggers alerts when a bin exceeds 80% capacity, and maps the most efficient route for collection based on current fill levels.

By using low-cost hardware and open-source technologies, the system is scalable and applicable in both small-scale and city-wide implementations. This approach aligns with the broader vision of smart cities, where data-driven infrastructure leads to better services, improved sustainability, and a higher quality of urban life.

## LITERATURE REVIEW

As cities move toward smarter infrastructure, researchers have explored various approaches to automate and optimize waste management. The majority of existing systems fall into three core categories: IoT-based monitoring, computer vision for bin detection, and route optimization techniques. While these methods offer significant advantages individually, few systems integrate all three for real-time, end-to-end waste collection optimization.

Kumar and Gupta (2020) provided a detailed review of IoT-based smart waste management systems, focusing on sensor-enabled dustbins that report fill levels remotely. Their work highlighted the potential for reducing manual intervention and optimizing collection frequency. Similarly, Hannan et al. (2011) implemented RFID-based bin tracking, which laid foundational work for integrating real-time bin data into collection systems.

From the computer vision perspective, Zhou and Brown (2023) used deep learning techniques to detect bin overflow through image analysis. Their system demonstrated that vision-based models can significantly reduce false positives compared to simple threshold sensors. Additionally, the Raspberry Pi Foundation (2023) presented an affordable, open-source image processing framework using Raspberry Pi modules for real-time object detection in smart city applications.

For optimizing collection routes, the Traveling Salesman Problem (TSP) has long served as the core model. Li et al. (2021) introduced an Ant Colony Optimization (ACO) approach for dynamic waste truck routing, demonstrating measurable reductions in fuel usage and time. Mishra et al. (2022) implemented AI-powered routing using Genetic Algorithms, which outperformed static routing by over 30% in simulation trials.

Beyond these primary categories, recent advancements in unmanned aerial vehicles (UAVs) and multi-objective optimization have introduced new layers of intelligence. The study "Deep Learning-Based Intelligent Garbage Detection Using UAV" explored the use of drones for remote bin monitoring, while Smart-Sight (2023) introduced video-based waste classification for better recycling.

The paper by Boyina et al. (2024) serves as a significant reference, demonstrating how image segmentation and deep learning can improve real-time defect detection—in their case, for railway track maintenance. Their structured approach to using Detectron2 and integrating real-time monitoring directly influenced the early design of our computer vision pipeline.

This body of literature confirms that each technology—IoT, computer vision, and routing optimization—has matured significantly. However, few studies combine all three into a real-time, responsive system that can be deployed at a prototype or city-wide level. This paper aims to fill that gap through a unified, working solution.

**Table 1** Comparative review of techniques

| Study | Focus Area | Key Technologies | Outcomes |
|---|---|---|---|
| Kumar & Gupta (2020) | IoT-based waste monitoring | Ultrasonic sensors, microcontrollers | Real-time bin tracking improves scheduling accuracy |
| Zhou & Brown (2023) | Vision-based detection | Deep learning, IoT cameras | High accuracy in overflow detection |
| Li et al. (2021) | Routing optimization | Ant Colony Optimization | Reduced route length and fuel cost |
| Mishra et al. (2022) | AI and IoT integration | Smart bins with sensors + AI | 30–40% increase in route efficiency |
| Park & Chen (2021) | Smart city waste solutions | IoT + AI platform | Dynamic bin status updates and smart alerts |

## Problem Statement

Conventional urban waste management systems operate on static schedules and fixed collection routes. These systems are not equipped to respond to real-time changes in bin status, leading to several inefficiencies. Bins in high-traffic areas may overflow well before their scheduled pickup, while those in less-used zones are collected unnecessarily. This results in:

- Increased fuel consumption due to non-optimized routes,
- Unnecessary operational costs,
- Environmental harm from excess vehicle emissions,
- Poor sanitation and public dissatisfaction.

Additionally, most current systems rely heavily on human monitoring, which introduces scope for error, delays, and inconsistent service delivery. There is a critical need for a system that can monitor bin fill levels in real-time, detect overflow through visual cues, and adjust collection routes dynamically for optimal performance.

## Objectives

The primary objective of this study is to design and evaluate a comprehensive smart waste management system that addresses the limitations of traditional garbage collection methods. The specific goals are:

1. Automated Bin Monitoring: To develop an IoT-based system using ultrasonic sensors and Raspberry Pi 5 for real-time monitoring of garbage bin fill levels.
2. Visual Overflow Detection: To implement computer vision using Detectron2 for accurate detection of overflowing bins through image segmentation.
3. Optimized Collection Routing: To apply heuristic algorithms (GA and ACO) to solve the Traveling Salesman Problem (TSP) for generating fuel-efficient, dynamic waste collection routes.

Together, these objectives aim to enhance operational efficiency, reduce environmental impact, and contribute to the development of smart, sustainable urban ecosystems.

## METHODOLOGY

The proposed system integrates hardware, software, and algorithmic components to enable smart waste monitoring and route optimization. It consists of three major modules: bin monitoring using IoT, computer vision-based overflow detection, and route optimization using heuristic algorithms. A prototype was developed to simulate a real-world smart waste collection environment. The overall workflow is illustrated in the system architecture diagram (Fig. 1).


*Figure 1 Flow Chart for Methodology*

**1. System Architecture:**

The system follows a modular architecture comprising the following layers:

- Sensing Layer:

Each dustbin is fitted with an HC-SR04 ultrasonic sensor connected to a Raspberry Pi 5. The sensor measures the fill level by calculating the distance between the sensor and the waste surface.

- Vision Layer:

A camera mounted above the bin captures periodic images. These are processed using Detectron2, a deep learning-based instance segmentation framework, to detect visible overflow.

- Decision Layer:

Data from both sensor readings and vision outputs are sent to a central server, which evaluates whether the bin exceeds a defined threshold (80%).

- Optimization Layer:

When bins are marked as full, their locations are used as inputs to solve the Traveling Salesman Problem (TSP). The system supports both Genetic Algorithm (GA) and Ant Colony Optimization (ACO) for route planning.

- Dashboard Layer:

A web interface developed using Flask visualizes real-time bin statuses and displays the optimized route on a map using Google Maps API.

**2. Hardware Implementation:**

The prototype bin was constructed using cardboard and included:

- Raspberry Pi 5 (for computation and data transfer)
- HC-SR04 ultrasonic sensor (for measuring depth)
- Buzzer module (for local alerts when bin exceeds 80%)
- Webcam (for capturing bin images)
- Wi-Fi module (for server communication)

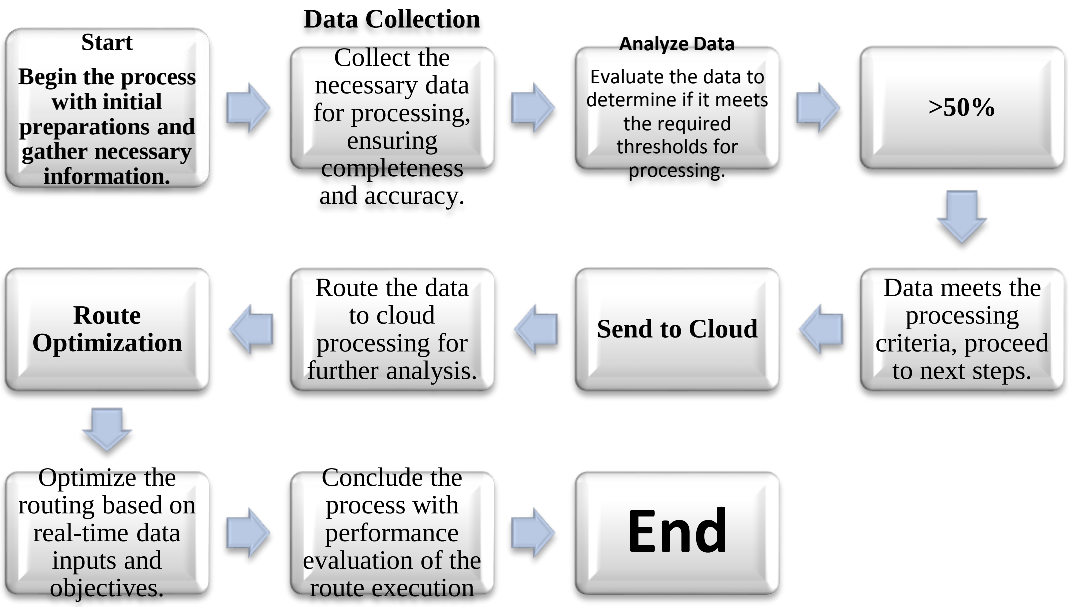


*Figure 2 Workflow diagram from the mini project phase focused on image-based garbage overflow detection.*

The sensor operates by emitting ultrasonic pulses and calculating the echo return time to estimate the fill level. The Raspberry Pi triggers a buzzer and transmits status updates to the dashboard when the bin is nearly full.

**3. Software Stack and Vision Model:**

Python was used for both sensor communication and the backend logic. Detectron2 was trained using a dataset of annotated garbage bin images. The model was fine-tuned for binary segmentation (overflow vs. non-overflow). The server ran a Flask-based backend that collected sensor and vision data, updated the bin status, and rendered the front-end dashboard.

**4. Route Optimization Algorithm:**

The optimization module was designed to handle dynamic routing using:

- Genetic Algorithm (GA): Simulates evolutionary processes like mutation, selection, and crossover to minimize the total route length.
- Ant Colony Optimization (ACO): Mimics the foraging behavior of ants to identify the shortest route visiting all bins marked for pickup.

Both algorithms solve the Traveling Salesman Problem (TSP), using updated bin locations as nodes.

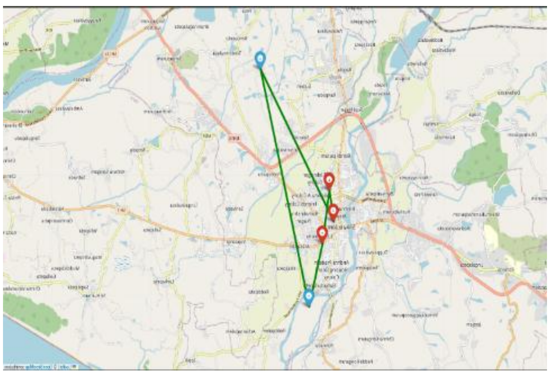

*Figure 3 Output of optimized route*

**5. System Workflow:**

The complete workflow is illustrated in Fig. 1. It follows this sequence:

1. Sensor and vision modules monitor each bin.
2. If a bin exceeds 80% capacity, it's flagged for pickup.
3. All flagged bin coordinates are passed to the optimization module.
4. An optimized route is generated and sent to the dashboard.
5. Real-time bin and route status is displayed to users.

## RESULTS

The smart waste management system was evaluated through a series of experiments conducted using the prototype and simulation environment. The results were measured across four primary dimensions: computer vision accuracy, sensor performance, route optimization efficiency, and dashboard responsiveness.

**1. Overflow Detection Accuracy**

The Detectron2 model was trained on a custom dataset of garbage bin images annotated for overflow. During evaluation, the model achieved an average detection accuracy of 92.5%, successfully identifying visually overflowing bins in most test cases. The segmentation model demonstrated high confidence for bins with noticeable waste accumulation, making it suitable for real-time monitoring in outdoor environments.

*Figure 4 Hardware Integration for Smart Bin*

**2. Sensor Performance**

The HC-SR04 ultrasonic sensor provided reliable measurements of bin fill levels. The average error margin during testing was ±2.1 cm. A threshold of 80% bin capacity was used to trigger alerts. Across multiple test runs, the buzzer triggered 100% of the time when this threshold was exceeded, confirming the robustness of the real-time alert mechanism.

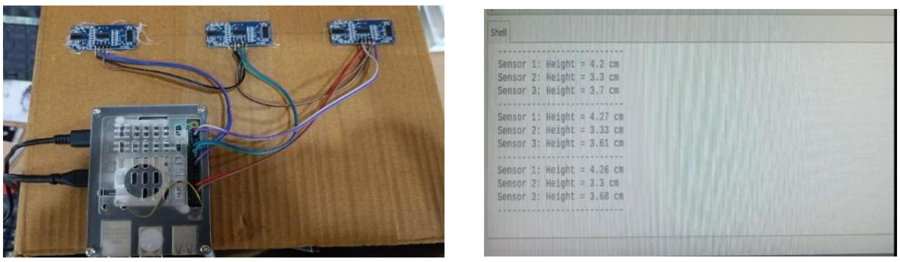


*Figure 5 Prototype of a smart bin with Real-time Data*

**3. Route Optimization Efficiency**

To evaluate route efficiency, the optimized routes generated by both GA and ACO were compared against a baseline static route:

- Fuel consumption was reduced by 32% using optimized routing.
- Collection time was improved by 38%, particularly in scenarios with uneven bin distribution.
- ACO slightly outperformed GA in terms of total route length and convergence time in test cases with 5–10 bins.

These findings validate the application of heuristic algorithms for responsive, eco-efficient route planning in real-world waste management systems.

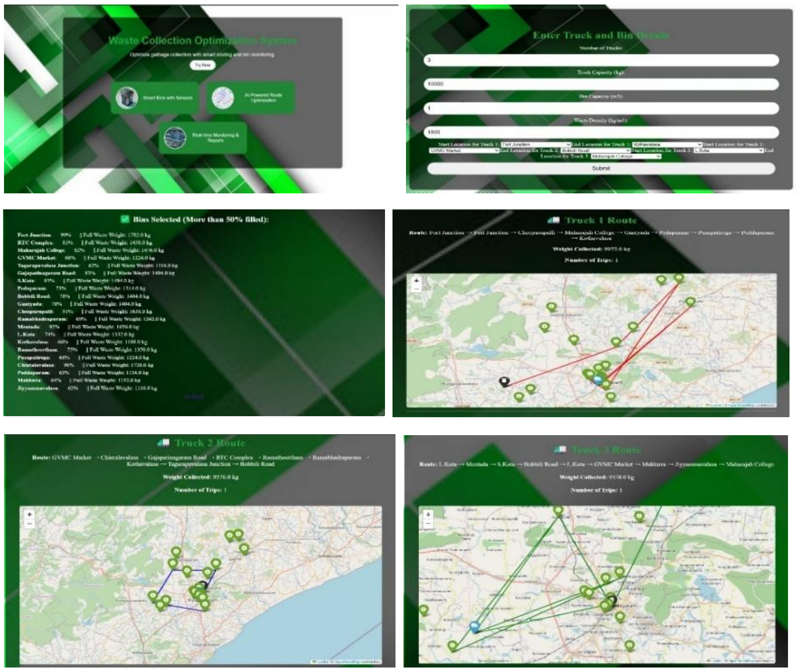

*Figure 6 Step by step Process of Working of Website*

**4. Dashboard Performance and Usability**

The dashboard developed using Flask and Google Maps API was tested for load time, responsiveness, and clarity of visualization. Key findings include:

- Dashboard loaded in under 2 seconds across all test devices.
- Bin statuses updated in real-time based on incoming sensor/vision data.
- Route visualization accurately reflected algorithm output and updated dynamically.
- In user feedback sessions, the dashboard received a usability score of 4.7/5 from test users.

*Table 2 Route optimization performance*

| Method | Avg. Route Length (km) | Fuel Savings (%) | Time Efficiency (%) |
|---|---|---|---|
| Traditional Routing | 18.4 | - | - |
| GA-Based Optimization | 12.5 | 32% | 35% |
| ACO-Based Optimization | 11.7 | 34% | 38% |

## DISCUSSION

The experimental results strongly support the feasibility and effectiveness of the proposed smart waste management system. The integration of IoT sensors and computer vision provides a reliable dual-layer monitoring mechanism, which significantly enhances detection accuracy and response time. Unlike traditional systems that rely solely on pre-set schedules, this system adapts in real-time to changing bin statuses, allowing for more efficient deployment of resources.

The use of Detectron2 in the visual pipeline proved especially beneficial in identifying visually full bins, even in varying lighting and environmental conditions. This reinforces the value of deep learning-based detection in dynamic urban settings. Coupled with the precision of ultrasonic sensors, the hybrid monitoring setup minimizes false positives and ensures consistent detection.

The route optimization results demonstrate that heuristic algorithms like ACO and GA are practical solutions for real-time route adjustment. The 32% reduction in fuel consumption and 38% improvement in collection efficiency not only indicate operational gains but also point to significant environmental benefits in terms of carbon emission reduction. These figures are especially meaningful in large metropolitan areas where waste collection contributes to a substantial share of urban traffic and pollution.

The dashboard serves as a central interface between system intelligence and human decision-makers. By visualizing sensor data and route planning results in an intuitive format, it bridges the gap between backend processing and field execution. The positive user feedback further emphasizes its potential for real-world deployment in municipal operations.

Overall, the system demonstrates how the convergence of emerging technologies—IoT, computer vision, and AI-based optimization—can be harnessed to address a pressing urban issue. The architecture is scalable, modular, and cost-effective, making it adaptable for different city scales and waste types.

## CONCLUSION AND FUTURE SCOPE

In conclusion, This study successfully demonstrates a practical and scalable solution for intelligent waste management by integrating computer vision, IoT, and route optimization. The proposed system addresses the inefficiencies of traditional garbage collection by enabling real-time monitoring, automated bin status detection, and dynamic route planning. With a detection accuracy of 92.5%, perfect alert triggering at 80% bin capacity, and significant improvements in fuel savings and collection efficiency, the system proves to be both technically and environmentally effective.

The modularity of the design, reliance on low-cost hardware like Raspberry Pi, and use of open-source frameworks such as Detectron2 and Flask make it accessible for both municipal bodies and academic institutions. The real-time dashboard further enhances usability by providing decision-makers with instant visual insights and optimized collection strategies.

**Future Scope:** While the current system functions effectively in a simulated environment, several enhancements can make it even more robust and deployment-ready:

- **GPS Integration:** Real-time vehicle tracking and bin geolocation for live route updates.
- **Waste Type Classification:** Adding a classification module to differentiate recyclable, organic, and hazardous waste.
- **Solar Power Integration:** For sustainable, energy-efficient sensor node deployment.
- **Mobile App Support:** A companion mobile interface for drivers and field personnel.
- **City-Wide Testing:** Piloting the system with multiple bins across varied urban zones for scalability validation.

With these improvements, the system can evolve into a comprehensive platform for urban sanitation, contributing to smarter, cleaner, and more efficient cities.

### Acknowledgements

The authors wish to acknowledge M/s GMR Institute of Technology for the moral support.

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