Annals of Process Engineering and Management

www.apem.reapress.com

Ann. Proc. Eng. Manag. Vol. 1, No. 1 (2024) 26–32.

Paper Type: Original Article

IoT-Enabled AI Solutions for Efficient Smart City Waste Management

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Citation:

Received: 09 April 2024 *Revised: 11 June 2024* *Accepted: 28 July 2024*	Raj Sah., R. (2025). IoT-enabled AI solutions for efficient smart city waste management. *Accounting and auditing with application, 1*(1), 26-32.

Abstract

The rise in urbanization has resulted in considerable challenges regarding waste management in smart cities, including inefficient collection techniques, overfilled trash bins, and increasing operational expenses. Conventional waste management approaches lack the necessary intelligence and adaptability to handle the constantly changing dynamics of urban waste generation. This article outlines a comprehensive approach that leverages Artificial Intelligence (AI) and the Internet of Things (IoTs) to enhance waste management in intelligent urban environments. Merging AI-driven data analytics with IoTs-connected sensors and devices allows for real-time monitoring of waste levels and the development of predictive models for collection schedules, ultimately leading to more efficient and sustainable waste management practices. The suggested strategy employs a network of smart trash bins fitted with IoTs sensors to track elements like fill levels, weight, and temperature. The information gathered is transmitted via Low-Power Wide-Area Networks (LPWANs) to a cloud-based platform for immediate analysis. AI techniques, including machine learning models for predictive maintenance and pattern recognition, are utilized to optimize collection routes and schedules based on anticipated waste generation trends. Moreover, computer vision technologies are implemented to automate the sorting of waste and enhance recycling efforts. The introduction of the AI-driven IoTs system has considerably boosted the efficiency of waste management. Case studies indicate that the frequency of waste collection has been reduced by as much as 40%, operational costs have dropped by 30%, and recycling rates have improved by 25%. Additionally, the system has effectively minimized overflowing garbage bins, thereby enhancing public health and environmental responsibility. These findings underscore the potential of AI and IoTs technologies to transform waste management in smart cities, fostering greater adaptability, cost-effectiveness, and environmental sustainability. The method proposed serves as a foundation for future developments in smart city infrastructure and supports more sustainable urban expansion.

Keywords: Artificial intelligence, Internet of things, Smart city, Waste management, Data analytics, Predictive maintenance, Environmental sustainability.

1 | Introduction

The ever-increasing global population is leading to numerous challenges, with one of the most pressing being the rise in waste generation. This waste can take various forms, such as food waste, material waste, industrial

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by-products, household items, and more. If not appropriately managed, these waste materials can harm the environment, posing risks to public health and natural ecosystems [1]. Consequently, waste management is a critical issue that demands urgent attention and practical solutions.

Waste management is not just about disposing of trash properly. It also involves monitoring waste production, collecting and transporting waste, and processing it in ways that minimize environmental impact. The ideal waste management strategy prioritizes waste prevention, reusing materials, recycling, energy recovery, and disposal as the least preferred option. With the increasing volume of waste generated, handling these processes is becoming more complex and costly [2]. The lack of efficient waste management systems in many areas often results in waste being left in open spaces or bodies of water, accumulating into unsanitary heaps that release toxic gases and unpleasant odors.

Global waste production is projected to grow significantly due to rapid urbanization and population growth. According to the World Bank, annual waste generation is expected to reach 3.4 billion tonnes by 2050, with East Asia and the Pacific alone producing around 714 million tonnes [3]. This alarming forecast highlights the urgent need for better waste management strategies to reduce the adverse effects on human health and the environment. The types of waste requiring management include organic waste, industrial waste, medical waste, electronic waste, nuclear waste, commercial waste, green waste, and recyclable materials.

Traditional waste management methods, which often involve manual processes, face several challenges, such as inefficient collection schedules, overfilled or underfilled bins, unoptimized vehicle routes, and difficulties in waste sorting. Without modern technologies, the process remains labor-intensive, costly, and prone to errors, ultimately making it ineffective in handling the growing volume of waste. *Fig. 1* shows that unattended waste is deposited in water, land and roads.

Fig. 1. Soiling of land and roads by unattended waste in water.

2 | Objectives

The primary objective of this paper is to explore the application of Artificial Intelligence (AI) and Internet of Things (IoTs) technologies in smart city waste management, aiming to optimize collection schedules, reduce operational costs, and improve environmental sustainability. The study seeks to present a comprehensive solution that integrates AI algorithms and IoTs-enabled devices to address current challenges in waste management systems [4]. It also aims to evaluate the effectiveness of such solutions through case studies and discuss potential barriers to implementation.

3 | Methodology

We employed several research methods and techniques to develop a new waste management solution. The primary approach involved a comprehensive literature review conducted over a set period. We reviewed various sources, including research articles, journal papers, white papers, conference proceedings, online blogs, and specialized websites focusing on smart waste management.

Specific keywords, such as smart city, smart waste management, waste handling, waste generation, and waste recycling, were used to find relevant information. The literature we gathered was analyzed based on several factors, including the publication year, the proposed solutions for smart waste management, current practices used worldwide, and new strategies implemented in modern smart cities. We also considered the associated costs, workforce requirements, and infrastructure for different waste management approaches.

In addition to the literature review, we examined interviews with subject matter experts, researchers, and professionals in smart waste management. We also conducted a few interviews with industry professionals to gather their insights on existing waste management methods and their suggestions for potential improvements. Lastly, we performed experiments, including simulations and prototype development, to create lab-level proof-of-concept models for the proposed solution. These tests helped us evaluate the system's efficiency and effectiveness in meeting the project's objectives.

4 | Related Works

The rapid growth of urbanization and industrial activities has led to increasing waste generation, posing serious environmental and health risks. This has made waste management a critical focus area for researchers and engineers worldwide working to develop and enhance smart waste management systems. Several notable studies have contributed to this field. Hong et al. [5] developed an IoTs-based Smart Garbage System (SGS) that uses battery-powered bins connected through a wireless mesh network.

Their year-long pilot project demonstrated a significant 33% reduction in food waste through efficient monitoring and management. Bueno-Delgado et al. [6] proposed an optimal planning algorithm using Net2Plan, an open-source tool traditionally used for communication networks. When applied to waste collection in Cartagena, Spain, their system effectively minimized the number of collection trucks needed, thereby reducing fuel consumption and CO2 emissions.

Another innovative approach came from Glouche and Couderc [7] who implemented RFID-tagged smart bins for automatic waste identification and tracking. Their system improved waste sorting efficiency without requiring external information systems. Oralhan et al. [8] combined IoTs technology with data mining to create smart containers with sensors measuring temperature, CO_2 levels, and fill status.

Using ant colony optimization for route planning, their system achieved 30% cost savings in waste collection while reducing environmental impact. Finally, Popa et al. [9] developed a fully automated waste collection system using the Azure platform. Their solution enabled real-time monitoring of bin status and route optimization through IoTs sensors and cloud-based analytics [10]. These studies demonstrate how modern technology can transform traditional waste management into more efficient, environmentally friendly systems.

5 | Deep Dive into Modern Waste Management

Smart cities prioritize waste management as a critical service, leveraging advanced technologies to minimize environmental impact. This modern approach encompasses everything from collection to final disposal, utilizing innovations in IoTs, analytics, and smart sensors to create efficient, sustainable systems [11].

5.1 | Core Components of Modern Waste Management

The system relies on five key technological pillars:

I. Smart fill-level monitoring: modern waste bins equipped with sensors provide real-time fill-level data, enabling collection teams to respond only when necessary. This targeted approach significantly improves operational efficiency by eliminating unnecessary collection runs [12].

II. Automated collection systems: integrating autonomous vehicles and robotic arms has revolutionized waste collection. These systems operate with minimal human intervention, increasing efficiency and safety while reducing operational costs and collection time.

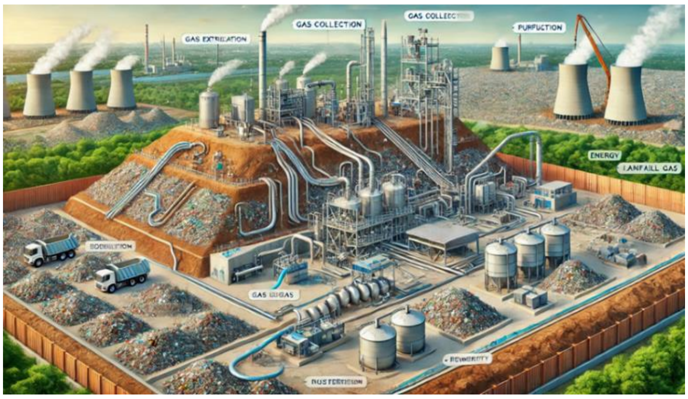

Fig. 2. Solid waste landfill gas-to-energy systems.

III. Advanced landfill technology: contemporary landfills employ sophisticated engineering solutions that comply with environmental regulations. These facilities focus on methane capture and ecological protection, using advanced monitoring systems to ensure safety and compliance.

IV. Waste-to-energy conversion: organic waste materials can be converted into valuable energy resources, including food scraps and agricultural byproducts. These facilities transform waste into usable energy through biogas digesters, thermal converters, and microturbine technology, creating a sustainable cycle of resource utilization.

V. Eco-friendly operations: the system promotes environmental sustainability through natural gas-powered collection vehicles, timely waste removal to prevent harmful emissions and efficient recycling processes that reduce carbon footprint through optimized operations.

Combining these elements creates a comprehensive waste management solution that maximizes resource efficiency while minimizing environmental impact. This system represents a significant advancement in urban waste management through automated monitoring, efficient collection, and sustainable processing.

6 | Smart Waste Management System: iSmartWMS

To address the main challenges in waste management while ensuring operational efficiency, we propose a cloud-based, IoTs-driven solution called iSmartWMS. This smart waste management system uses secure, encrypted communication and a multi-layered client-server architecture to manage the entire waste management process. *Fig. 3* shows the key components of iSmartWMS.

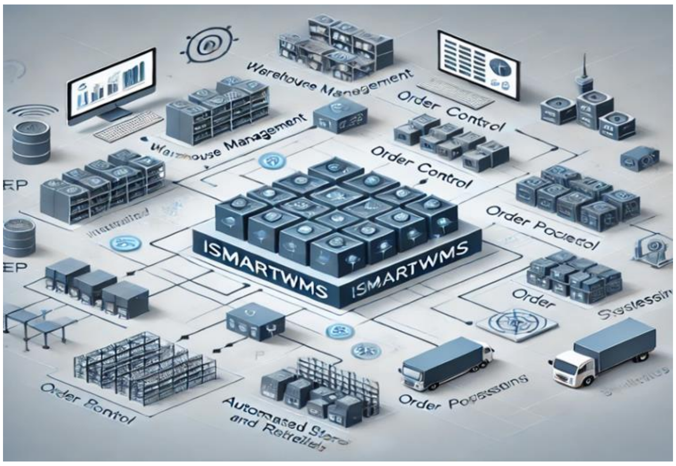

Fig. 3. High-level block diagram of proposed iSmartWMS.

6.1 | Smart Trash Bin

Smart trash bins go beyond regular waste bins by incorporating sensors that provide information about fill levels and maintenance needs. These bins can store wet and dry waste and share data online. The primary sensors used include:

Ultrasonic sensors

These measure how full the bin is using sound waves. The data is sent to the system using GSM or IoTs networks such as LORA, MQTT, or COAP. The sensors are compact and lightweight and can last over two years on battery power.

RFID tags

RFID tags are used to track bins and verify services. RFID tags do not require a line of sight and can be easily installed in plastic or metal bins.

Load cells

Installed at the bottom of the bin, load cells measure weight to indicate if a bin has reached its maximum capacity for safe pickup.

Image sensors

Cameras inside the bin capture images to assess the bin's fill level and contents, which is particularly useful for bulky or hazardous waste.

Temperature and humidity sensor

These monitor conditions inside bins that store industrial waste, ensuring timely servicing to prevent risks.

Gas sensors

Detect harmful gases emitted from certain waste types, such as chemical or medical waste, triggering alerts when gas levels exceed safe limits.

The trash bin controller collects all sensor data and securely communicates it to the iSmartWMS server. The controller also allows two-way communication, enabling the server to request specific data when needed.

6.2 | Smart Waste Truck

Smart Waste Trucks (SWTs) are integral to iSmartWMS, collecting and transporting waste efficiently. These trucks feature:

I. Robust containers for separate storage of wet and solid waste.

II. Robotic arms for automated waste collection.

III. Sensors for waste level detection, air quality monitoring, and temperature checks.

IV. 24/7 secure wireless communication, GPS tracking, and real-time communication with the management server.

The SWTs receive alerts and optimized route information to streamline waste collection.

6.3 | iSmartWMS Server

The iSmartWMS server is the central hub of the system, managing communication with trash bins, trucks, landfill stations, recycling plants, and administrative staff. Its main functions include:

I. Monitoring the fill levels and condition of all bins.

II. Providing route optimization for waste trucks.

III. Storing waste-related data and generating alerts during emergencies.

IV. Running data analytics for waste management insights, such as the number of bins that need servicing or the amount of waste recycled over time.

V. Offering a web interface for administrators to monitor real-time data and generate reports.

6.4 | iSmart WMS Database

The database securely stores all waste management data, using encryption to protect information. It can be built on open-source platforms like MySQL or MongoDB or hosted on cloud services for better accessibility.

6.5 | Recycling Plant Controller

This controller tracks recycled waste by gathering data from scales and operator inputs. It provides regular updates to the iSmartWMS server, including:

I. Daily, weekly, monthly, and yearly data on the amount of waste received and recycled.

II. Information about the types of materials recycled.

III. Status reports for normal, alert, or emergencies.

6.6 | Landfill Station Controller

The landfill controller monitors the amount of waste deposited at landfills. It communicates regularly with the iSmartWMS server, reporting:

I. Daily, weekly, monthly, and yearly landfill data.

II. Gas emissions generated by the waste.

III. Status updates indicating normal operations, alerts, or emergencies.

Overall, iSmartWMS integrates these components to provide a smart and efficient solution for waste management, enhancing operational efficiency and safety while reducing environmental impact.

7 | Results and Discussion

Due to time and budget limitations, the iSmartWMS system was explored mainly at a conceptual level, making it impossible to implement the full system. However, a simplified version was created and tested in a lab environment. Simulated waste collection data was used to assess the system's performance in data analysis, generate alerts for emergencies, and detect when trash bins needed immediate servicing.

The system's ability to optimize waste collection routes was successfully tested using Google Maps and simulated trash bin data. A secure web interface was developed for authorized users to access a dashboard displaying relevant data. The user-friendly interface was built with C#, while MySQL was used for the database, which worked effectively.

Although the system was tested with a limited dataset, the results were promising. User feedback during lab testing was positive, with many appreciating the solution.

8 | Conclusions

The proof-of-concept testing for the iSmart WMS system showed that it successfully performed all intended functions. However, the system's full potential couldn't be assessed because the testing was done with limited data and lacked real-world waste data. This makes it difficult to evaluate the overall performance of iSmart WMS as a complete Smart Waste Management solution.

Despite these limitations, the positive results suggest that iSmartWMS could be very effective for smart waste management if fully implemented. To truly harness its benefits, it's recommended that the complete system be developed according to the defined requirements and components.

Author Contribution

Rahul Raj Sah contributed to the conceptualization, research, and writing of this article. He focused on the integration of AI and the IoTs to enhance waste management in smart cities and analyzed the impact of these technologies on urban sustainability.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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