СРПСКО ДРУШТВО ЗА ПУТЕВЕ 1934

Пут и саобраћај
Journal of Road and Traffic Engineering

Journal homepage: www.putisaobracaj.rs

Smart Bin for Urban Energy Recovery Optimisation

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ARTICLE INFO

DOI: 10.31075/PIS.71.04.03
Professional paper
Received: 17.09.2025.
Accepted: 12.10.2025.
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Keywords
Smart Waste Management
IoT Architecture
Energy Recovery
TLBO Optimisation
Biogas
Discrete Event Simulation

ABSTRACT

Rapid urbanisation in developing countries has intensified pressures on municipal waste management systems while increasing demand for sustainable energy solutions. This study presents the design and simulation-based evaluation of an integrated Autonomous Waste Management System (AWMS) that combines smart waste collection with biogas-based energy recovery. The proposed architecture consists of IoT-enabled Smart Waste Bins, Autonomous Car Bases for waste transport, and an Administrative Centre responsible for real-time monitoring, routing decisions, and system coordination. Teaching–Learning-Based Optimisation (TLBO) is applied to dynamically optimise collection routes based on live sensor data. System performance is evaluated using a Discrete Event Simulation (DES) framework implemented in Python and SimPy over a 30-day period for a hypothetical urban community. Multiple waste-generation scenarios are analysed, and statistical tests are used to compare the AWMS with a conventional fixed-schedule system. Results indicate improvements in collection efficiency, reductions in collection time and transport energy use, increased biogas yield, and lower greenhouse gas emissions. The system also supports organic fertiliser recovery from digestion by-products. These findings demonstrate the scalability, operational effectiveness, and environmental benefits of integrating real-time optimisation and energy recovery within autonomous waste management systems, particularly in rapidly growing urban contexts.

1. Introduction

Rapid urban growth in many developing countries has intensified long-standing challenges in municipal solid waste management. Conventional collection systems tend to follow rigid schedules, depend heavily on manual labour, and require considerable fuel consumption. These constraints frequently lead to delayed pickups, operational inefficiencies, and environmental burdens. Advances in Internet of Things (IoT) technologies, artificial intelligence, and autonomous mobility present opportunities to redesign these processes by enabling real-time monitoring and more responsive routing. However, most existing approaches concentrate primarily on the collection cycle and do not incorporate broader functions such as dynamic optimisation or energy recovery.

This study introduces an integrated Autonomous Waste Management System (AWMS) that brings together IoT-enabled smart bins, autonomous logistics, and a biogas-based Waste-to-Energy (WtE) subsystem. The system is designed to capture live operational data, adjust routing through heuristic optimisation, and convert organic waste into usable energy. By combining these components within a single framework, the AWMS aims to improve operational efficiency, support environmental sustainability, and provide a scalable model suitable for rapidly expanding urban communities

2. Methodology and Results

This study adopts a systems-based engineering approach to design, simulate, and evaluate an Autonomous Waste Management System (AWMS) that integrates smart waste collection with biogas-based Waste-to-Energy (WtE) conversion. The methodology encompasses four major components: system architecture design, IoT-enabled communication framework, energy generation subsystem, and simulation-based scenario modeling using Discrete Event Simulation (DES).

2.1. System Architecture

An Autonomous Waste Management System (AWMS) is a system that includes three interconnected subsystems that are: Smart Waste Bins (SWBs), Autonomous Car Bases (ACBs), and an Administrative Centre (AC). They are collectively useful in real-time monitoring, adaptive routing and energy recovery. The subsystems perform distinct functions, and the combination of all the subsystems forms a harmonious sequence of work processes between collecting waste and transforming it into energy.

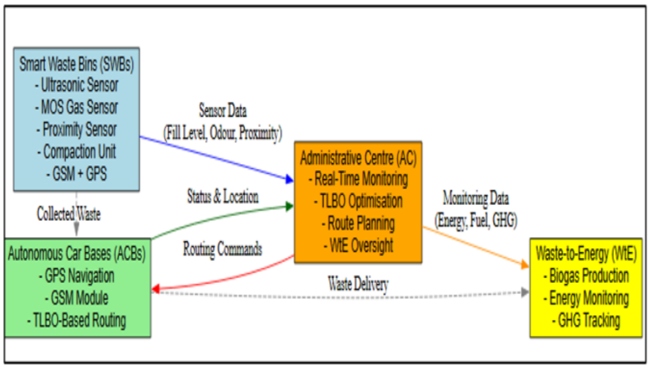

Figure 1. *Smart Waste Bin Architecture*

Smart Waste Bins (SWBs)

The SWB architecture is depicted in Fig. 1. All bins feature a solar energy source and LiFePO4 batteries, providing stable performance under all conditions. The bin has an ultrasonic sensor to measure fill level, a MOS sensor to measure odour gases such as methane and hydrogen sulfide, and a proximity sensor to measure the presence of nearby people. The sensor data are transmitted by a GSM -GPS unit to the Administrative Centre (AC). An inbuilt compactor increases storage area, reducing the number of collections and enhancing productivity.

Autonomous Car Bases (ACBs)

ACBs are mobile robots which relocate waste in the SWBs to the central plant. They navigate with the help of GPS and communicate with the AC all the time with the use of GSM. They use preset routes, but Teaching-Learning-Based Optimisation (TLBO) modifies the routes on-the-fly and based on information provided by the SWBs. This allows the fleet to be flexible to evolving circumstances.

Administrative Centre (AC)

The AWMS decision-making engine is the AC. It collects the information of the SWBs and the ACBs, providing real-time information on the waste quantity, odour and pickup status. TLBO Optimisation and predictive analytics forecast the waste trends and optimise the efficient ACB routes. The Waste-to-Energy (WtE) system is also under monitoring by the AC, and it is to measure the biogas production, electricity production and the production of greenhouse gases. Such activities make the system as a whole efficient, including collection to energy recovery.

2.2 Framework of IoT and Communication.

The AWMS communication system is a system that provides an uninterrupted and real-time data flow between the Smart Waste Bins (SWBs), Autonomous Car Bases (ACBs), and the Administrative Centre (AC). The sensor readings (fill level, odour intensity, GPS coordinates) are transmitted by each SWB via the GSM connectivity via lightweight protocols (MQTT, HTTP) as well. The choice of these protocols was based on their low bandwidth and ability to survive in distributed, sensor-intensive environments and guarantee the high transfer of data even when the network becomes unstable.

These streams of data are sent and interpreted by the AC using a time-triggered decision model. The system notifies a collection request when predetermined operational thresholds are met (e.g. a bin fill level of more than 75% or an odour level with an intensity of 4). This is followed by the optimisation of the routing operation using Teaching-Learning-Based Optimisation (TLBO) algorithm, which computes new routes of the ACBs taking into account the anticipated travel time, energy consumption and the priorities of the bins.

In order to ensure the reliability of the system, the communication layer has integrated security features such as encrypted transmission of data and verification of the device. The mechanisms guard against unauthorised access and secure the integrity of operational commands that are exchanged in the AWMS.

2.3. Waste-to-Energy Subsystem

Collected waste is conveyed to a central processing facility where it undergoes the following stages:

- **Pre-treatment:** Waste is sorted to remove non-biodegradable materials and shredded to increase surface area for microbial activity.
- **Anaerobic Digestion:** Shredded organic waste is processed in sealed digesters under anaerobic conditions. The digestion process consists of four stages—hydrolysis, acidogenesis, acetogenesis, and methanogenesis. These are maintained under controlled temperature and pH for optimal microbial action.
- **Biogas Handling and Energy Conversion:** The biogas (primarily methane) is stored in pressure-regulated tanks and used to power gas generators. The system produces approximately 6 kWh of electricity per cubic metre of biogas, which is sufficient to power local infrastructure and possibly supply excess to the grid.
- **Digestate Processing:** The remaining digestate is processed into organic fertiliser, contributing to the circular economy and reducing the environmental footprint.

2.4. Simulation and Scenario Design

Simulation Framework Overview

The simulation framework models the complete flow of waste from household generation through collection, transport, processing, and energy conversion. It evaluates how the integrated architecture behaves under different load conditions and provides a controlled environment for comparing performance outcomes. The scenarios were structured to reveal how the system responds to incremental changes in waste volume and to verify whether the operational advantages proposed in the conceptual model hold under dynamic urban conditions.

The simulation framework models the end-to-end process of the Autonomous Waste Management System (AWMS), from waste generation to energy recovery. As illustrated in Figure 2, waste is generated at the household level and moves through a series of operations — collection, transportation to community hubs, sorting and shredding, anaerobic digestion, and energy conversion.

To enhance the reliability of the comparative findings, statistical analyses were conducted using Python's SciPy and NumPy libraries. For performance indicators such as biogas yield, waste collection efficiency, and energy output, we calculated the mean and standard deviation over multiple simulation runs ($n = 30$ per scenario). Independent two-sample t-tests were applied to determine whether the observed differences between the AWMS and traditional system were statistically significant at a 95% confidence level ($p < 0.05$).

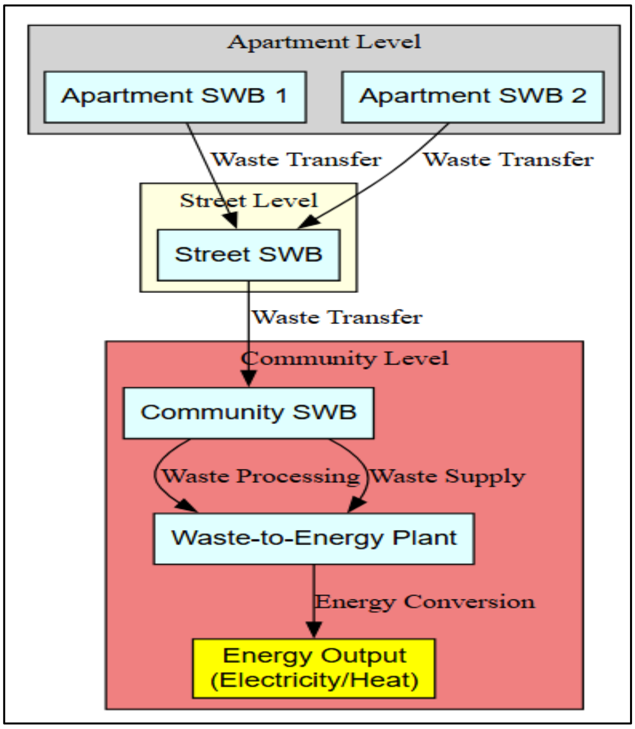

Figure 2. *Conceptual Framework of AWCS*

Biogas is produced from organic waste used for energy generation, while the remaining digestate is repurposed for agricultural or environmental use.

To evaluate the dynamic behaviour of the AWMS, a Discrete Event Simulation (DES) model was developed using Python and SimPy. The simulation spans a 30-day period and represents a hypothetical urban community of 3,000 to 4,000 residents. The model accounts for key processes including waste generation, smart bin data transmission, autonomous vehicle routing (using TLBO), digestion, and biogas-based energy conversion.

Three scenario categories were designed to test the system's scalability and performance under varying waste loads:

- Baseline Scenario: Daily waste generation of 1,500–2,600 kg, with 80% organic content.
- Scenario A: +2% increase in daily waste.
- Scenario B: +3% increase in daily waste.
- Scenario C: +5% increase in daily waste.

For each scenario, the simulation tracks and evaluates the following performance indicators:

- Waste throughput (kg/day)
- Biogas yield (m^3/day), based on an estimated yield of 0.311 m^3/kg.
- Electrical energy output (kWh/day), derived from the biogas.
- Route efficiency, based on TLBO-optimised pathfinding (time saved and fuel consumption).
- System responsiveness, measured through collection time lags and bin overflow events.

Simulation outputs confirm that daily biogas production ranged from 373 m^3 to 647 m^3, generating approximately 2,238 kWh to 3,882 kWh of electrical energy. These results are compared with traditional fixed-schedule waste collection methods to assess the proposed AWMS in terms of efficiency, scalability, and sustainability under real-world dynamics.

2.5. Results and Analysis

This section presents and analyses the simulation outputs generated from the Discrete Event Simulation (DES) model of the Autonomous Waste Management System (AWMS), which integrates Internet of Things (IoT) technologies, Waste-to-Energy (WtE) processing, and Teaching-Learning-Based Optimisation (TLBO). The performance of the AWMS was evaluated across multiple dimensions including waste throughput, energy generation, route optimisation, and environmental impact, and compared with conventional waste management systems.

2.6. Operational Performance

The AWMS exhibited high consistency and scalability across all simulated scenarios. As daily waste generation increased, the system adapted without any operational breakdown, processing the increased volume efficiently and proportionally converting it to energy. This confirms the system's capacity to maintain performance under variable loads, which is critical in real-world deployments where waste generation is non-uniform and seasonally affected. Table 1. provides a summary of the system's performance under the baseline condition and incremental increases of 2%, 3%, and 5% in daily waste generation. A linear relationship was observed between organic waste volume and biogas production, with corresponding increases in energy output. This supports the validity of the anaerobic digestion model used within the simulation and confirms the potential of the system to scale with urban population growth.

Table 1. *Waste, Biogas, and Energy Metrics by Scenario*

Scenario	Total Waste (kg)	Organic Waste (%)	Biogas Yield (m^3)	Energy Output (kWh)
Baseline	1,500–2,600	80%	373–647	2,238–3,882
+2% Increase	1,530–2,652	80%	380–660	2,280–3,960
+3% Increase	1,545–2,678	80%	384–668	2,304–4,008
+5% Increase	1,575–2,730	80%	391–679	2,346–4,074

The system demonstrated a 6.3% increase in energy output under the 5% scenario compared to the baseline, affirming its effectiveness in handling moderate increases in waste generation without compromising performance. Furthermore, the energy generated (up to 4,074 kWh/day) was sufficient to support basic energy needs for a small urban community, with potential excess for grid integration or off-grid applications.

2.7 Optimisation with TLBO

A Teaching Learning Based Optimisation (TLBO) framework facilitates routing performance in the AWMS by updating the movement of vehicles according to the prevailing operational conditions, instead of a set collection schedule. Based on live feeds of the Smart Waste Bins (SWBs) such as fill status, odour intensity, and geospatial data, the algorithm creates updated routes with the consideration of the estimated travel time, energy demand, and priorities of the bins. This dynamic mechanism allows the Autonomous Car Bases (ACBs) to react to the changes in the waste production and spatial distribution within the estate.

The results of simulation indicate the practical effect of TLBO technique as incorporated into the routing process. The optimised routes realised 18 percent decrease in the mean collection time and this permitted additional bins to be served within the identical time frame of operations. Energy consumption in transport became reduced by 12 per cent, which represents a higher direct and efficient vehicle movement. The cases of overflow dropped by a factor of 23 which means that the responsiveness to the bins that are near operational limits has been enhanced. These findings demonstrate how the algorithm is able to make routing decisions dynamically and able to aid more stable system behavior with variable load conditions.

The TLBO helps to enhance the overall trustworthiness of the AWMS by matching the collection activity with the needs of the real-time system and leads to the quantifiable increase of the working efficiency. Improvements noted also prove the usefulness of the heuristic optimisation in the autonomous waste management environment where the conditions constantly change and need to be acknowledged without human interference.

2.8 Comparative Evaluation

A comparative analysis was done to assess the working of the Autonomous Waste Management System (AWMS) in comparisons to a traditional fixed-timetable waste collection model. The comparison was concentrated on three main indicators, namely waste collection efficiency, biogas yield, and greenhouse gas (GHG) emissions, which have been selected because they were able to reflect operational, as well as environmental impacts. The results are concluded in Table 2: Efficiency and Environmental Impact Comparison.

Table 2: *Efficiency and Environmental Impact Comparison*

Performance Metric	Traditional System	AWMS	Improvement (%)	p-value
Waste Collection Efficiency	61% ± 3.4	95% ± 2.1	+34%	<0.001
Biogas Yield (m^3/day)	507 ± 15.6	647 ± 13.2	+27%	<0.001
GHG Emission Reduction	Baseline	-23%	-	-

The AWMS had various benefits in all metrics given in Table 2. With the AWMS, the efficiency of collection was 95% ± 2.1 with 61% being the traditional model. There was also a significant increase in the production of biogas as it increased to 647 ± 13.2 m 3/day as compared to 507 m 3/day. This growth is an indication of the ability of the system to dispose a greater percentage of organic waste into the Waste-to-Energy subsystem. Moreover, it achieved a reduction of about 23% in GHGI which was mainly a result of shorter routing routes, less fuel usage and less dependence on fixed, resource based collection schedules.

Independent two-sample t-tests were used in testing the differences among all of the tested indicators; the results statistically differed at the 95 percent confidence level ($p < 0.05$). Such results prove that the AWMS does not only increase the efficiency of operations, but also provides environmental improvements that are measurable. Collectively, the changes mentioned in Table 2 support the potential of the system as more sustainable and data responsive compared to traditional waste management practices.

2.9 Summary of Key Findings

- Scalability: The system scales effectively with increased waste input without performance degradation.
- Efficiency: Both waste collection and energy generation processes are significantly more efficient than those in legacy systems.
- Sustainability: The system contributes to GHG mitigation and supports circular economy principles via organic fertiliser recovery.
- Technological Relevance: The use of IoT and TLBO provides intelligent control, adaptive responsiveness, and real-time optimisation capabilities.

The statistical significance of the improvement observed underscores the reliability of AWMS performance across critical operational and environmental metrics.

2.10 Implementation Cost Analysis

A comparative cost analysis was conducted to evaluate the financial feasibility of deploying the AWMS against conventional waste management systems. The proposed AWMS requires higher capital investment: smart bins with sensors and solar units average $400 per unit (Zeb et al., 2019), autonomous car bases cost between $8,000 and $15,000 depending on configuration (Wahab et al., 2021), and a medium-scale biogas plant installation ranges from $25,000 to $100,000 (FAO, 2021). However, operational costs are substantially reduced due to savings in labour, fuel, and routing efficiency—estimated at 12–18% over fixed-schedule methods (Yadav et al., 2021).

In contrast, traditional systems incur lower upfront costs (typically <$30,000) but bear higher cumulative costs over time, especially from labour, fuel, and tipping fees. Using a simplified Total Cost of Ownership (TCO) model, the AWMS achieves breakeven within three years through energy sales (at approx. $0.10/kWh, or $4,000/month) and organic fertiliser reuse, making it increasingly cost-effective over time. These results align with findings by Fatimah et al. (2020) and Zeb et al. (2019), who highlighted the long-term economic and ecological value of integrated smart waste-to-energy solutions.

2.11 Limitations and Future Work

Despite the promising results, this study has certain limitations. First, the simulation assumes ideal environmental and operational conditions, such as uninterrupted GSM connectivity, optimal battery efficiency, and uniform waste generation patterns, which may not hold in real-world settings. Additionally, the absence of hardware prototyping means that potential hardware integration challenges, like sensor calibration or data latency, are not captured. Traffic variability and unforeseen urban events were also simplified in the model. Future work will incorporate hardware-in-the-loop simulations and pilot implementations to validate system robustness in diverse urban conditions.

3. Conclusion

The developed Autonomous Waste Management System (AWMS) in this research offers a viable and scalable infrastructure of this research in solving the problem of waste collection and energy recovery in the fast growing urban environment. The integration of IoT-based sensing, self-driving transportation, and biogas-driven energy transformations will make the system more responsive to waste collection activities and contribute to the increase in efficiency of resource utilization. According to the simulation results, the fixed-schedule systems have fixable gains in terms of operational efficiency and environmental performance compared to simulation results. These results suggest that the AWMS provides a solid base on which the real-world application and the further research on the issues related to smart and energy-saving waste management can be conducted.

Author Contributions A.D. Omiyale conceived the study and ran simulations; O.O.E. Ajibola and F.O. Ogunwolu provided technical input and review.

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