Chronicle of Bioresource Management 2026, 10(1): 007-011

Chronicle of Bioresource Management
An International E-magazine

March, 2026 Popular Article

DOI: HTTPS://DOI.ORG/10.23910/3.2026.6875

Artificial Intelligence (AI) in Waste Management: A New Era of Smart and Sustainable Systems

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Citation: Paul et al., 2026. Artificial Intelligence (AI) in Waste Management: A New Era of Smart and Sustainable Systems. Chronicle of Bioresource Management 10(1), 007-011. HTTPS://DOI.ORG/10.23910/3.2026.6875.

Data Availability Statement: Legal restrictions are imposed on the public sharing of raw data. However, authors have full right to transfer or share the data in raw form upon request subject to either meeting the conditions of the original consents and the original research study. Further, access of data needs to meet whether the user complies with the ethical and legal obligations as data controllers to allow for secondary use of the data outside of the original study.

Conflict of interests: The authors have declared that no conflict of interest exists.

Keywords:
Artificial intelligence, artificial neural networks, machine learning, smart waste management

Article History
Article ID: CBM6875
Received on 15th December 2025
Received in revised form on 11th February 2026
Accepted in final form on 23rd February 2026

Abstract

Rapid urbanization, population growth and changing consumption patterns have intensified the global waste crisis, placing immense pressure on conventional waste management systems. Artificial Intelligence (AI) has emerged as a transformative tool capable of improving efficiency, accuracy and sustainability across the entire waste management chain. This article reviews the role of AI in waste generation forecasting, smart collection, automated segregation, optimized transportation, disposal and real-time monitoring. Applications of machine learning, artificial neural networks, computer vision and Internet of Things (IoT)-based sensing are highlighted with practical examples. While AI-driven systems offer significant environmental and economic benefits, challenges related to data quality, infrastructure cost, privacy, cybersecurity and algorithmic bias must be addressed for large-scale adoption. Integrating AI with robust policy frameworks and capacity building can enable smarter, cleaner and more resilient waste management systems.

1. Introduction

The basic human needs of food, clothing and shelter have shifted significantly through the years, and the pursuit of comfortable living often results in increased waste generation due to higher consumption of resources and reliance on disposable products. Modern lifestyles characterized by increased consumption, packaging and disposability have resulted in a dramatic rise in waste generation across municipal, industrial, agricultural, healthcare and construction sectors. Inefficient handling of this waste contributes to environmental pollution, greenhouse gas emissions, public health risks and resource depletion (Kaza et al., 2018). AI has gained prominence in a short period of time due to the numerous applications previously unattainable in the area of waste management. Data analysis, automating and predicting capabilities enabled by AI can optimize every stage of waste management (Figure 1) from collection to recycling and disposal.

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Journal Home: *https://ojs.pphouse.org/index.php/CBM*

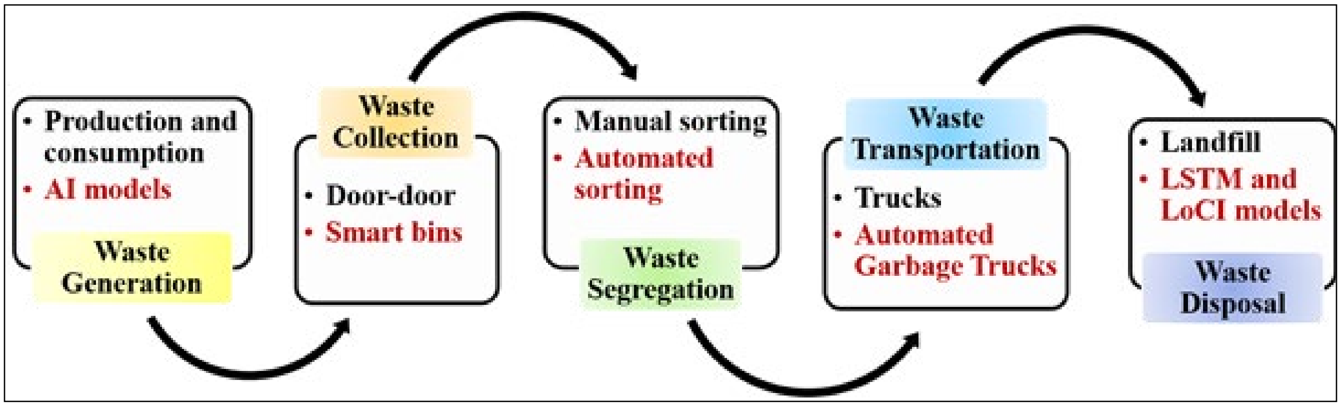

Figure 1: AI in different stages of waste management

AI-driven solutions can help municipalities and waste management companies minimize environmental impact, reduce costs, and improve efficiency. It has immense potential in improving recycling rates, reducing landfill use and contributing to a circular economy in which waste is minimized, and resources are used effectively (MacArthur and Cowes, 2019).

2. AI Across Various Stages of Waste Management

2.1. Waste generation forecasting

Urbanization, economic development and population growth are the natural causes of waste generation. It can be predicted using AI models ranging from simple linear regression to more advanced algorithms, such as Long Short-Term Memory (LSTM). Artificial Neural Network (ANN) is ideal for capturing nonlinear relationships in waste generation data based on factors such as population growth, consumption patterns and seasonal trends (Abbasi and El Hanandeh, 2016). Random forest model forecasts household or industrial waste generation based on various socioeconomic indicators, weather data and consumption patterns. LSTM and Recurrent Neural Network (RNN) models assess daily, weekly, monthly and yearly waste generation trends (Singh and Uppaluri, 2023). These models aid waste management authorities in anticipating future waste flows, resulting in a cost-effective and more appropriate waste management system.

2.2. Smart waste collection

Municipalities generally provide waste collection as a primary service. Smart recycling bins provide an alternative to the conventional garbage bins with numerous advantages with respect to improved hygienic conditions in deterring the breeding of disease-causing organisms and assessing the trash level in the bins. Robotic automation aids in the allocation of different waste types into their appropriate bins. It embodies a camera module that automatically monitors the trash filling level and a notification alerts the user to empty it when the bin reaches its capacity. With smart bins, increased efficiency of garbage collection could be achieved, thereby improving the city's overall environment (Longhi et al., 2012).

2.3. Automated waste segregation and sorting

Automatic sorting systems utilize robotics and machine learning to categorize waste accurately and enhance the efficiency of waste sorting, thereby replacing manual waste sorting. Developing AI algorithms that can learn the different types of trash we encounter requires extensive training. The AI platform identifies materials and determines their recyclability based on their colour, texture, size, brand labels, etc. Robotic arms employ AI algorithms to sort waste at speed and precision well beyond the capacity of humans by applying an ANN and a Convolutional Neural Network (CNN) automatically (Riyadi et al., 2024). The algorithms of Everest Labs are trained on a proprietary dataset containing over 5 billion recyclable objects. They can sort trash with 95% accuracy with their robotics platform, Recycle OS. The AI model developed by Glacier's is capable of distinguishing between the variants of similar-looking recyclable materials such as PET, HDPE, fiber, etc. High-power jet systems introduced by AMP are equipped with optical sensors, capable of picking 1000 trash items/min on conveyor belts moving at a speed of 600 feet/min.

2.4. Waste transportation and route optimization

Waste transportation is a critical operational component of municipal solid waste management, directly influencing fuel consumption, labour costs, greenhouse gas emissions and service reliability. Traditionally, waste collection vehicles follow fixed routes and schedules, often resulting in inefficient coverage, unnecessary fuel usage and delayed collection in rapidly growing urban areas. Recent advancements in Artificial Intelligence have enabled dynamic route optimization and automation, significantly improving transportation efficiency.

AI-based route optimization systems integrate real-time data from Global Positioning Systems (GPS), smart bin sensors, traffic conditions, weather forecasts and vehicle availability. Machine learning algorithms analyze these multi-source datasets to generate optimal collection routes that minimize travel distance, fuel consumption and collection time while maintaining service consistency (Ghiani et al., 2014). As illustrated in (Figure 2), AI-driven route optimization follows a cyclic process involving real-time data acquisition, algorithmic route planning, adaptive scheduling and continuous performance feedback. This adaptive approach allows waste collection fleets to avoid traffic congestion, hazardous zones and unnecessary trips, thereby reducing operational costs and environmental impacts.

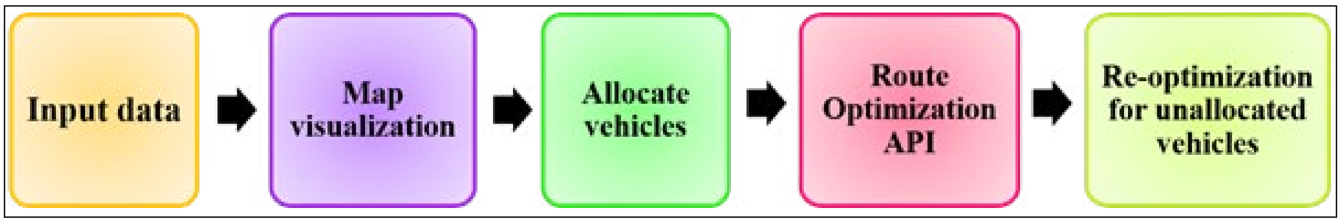

Figure 2: Process of AI-driven Route Optimization

In addition to route optimization, autonomous and semi-autonomous garbage collection vehicles represent a major technological advancement in waste transportation. These vehicles rely on pre-programmed GPS routes, sensor fusion technologies (LiDAR, cameras and proximity sensors) and AI-based decision-making systems to navigate safely through urban environments. Compared to conventional collection vehicles, automated garbage trucks reduce human exposure to hazardous waste, lower labour requirements, and enhance collection speed and consistency. A comparative overview of conventional and AI-enabled garbage collection systems is presented in (Table 1), highlighting improvements in labour efficiency, route planning, worker safety and recycling outcomes achieved through AI integration.

Table 1: Comparison between a Conventional vehicle and an Automated garbage truck

Conventional vehicle/ Truck	Automated garbage truck
• More workload on labors	• Reduced workload on labors
• Requires more staff on site	• Requires fewer staff on site
• Slower collection	• Faster collection
• High labour cost	• Lower labour cost
• Workers are exposed to infection and injuries	• Reduced risk of infections and injuries
• Inefficient route planning	• Optimized route planning
• Lower recycling rate	• Enhanced recycling rates

2.5. Waste disposal and resource recovery

Around the World, almost 40% of the waste is disposed of in landfills, 19% undergoes material recovery through recycling and composting, and 11% is being treated through modern incineration. AI models allow the prediction of the calorific value of waste and enhance the operational efficiency of incineration facilities. LSTM models assist in optimizing, maintaining and managing variables such as airflow, temperature, emissions, etc. It also improves the response time and stability of the incineration system (Chen et al., 2022).

AI-based solutions to landfill challenges include methane monitoring and management, leachate prevention and space optimization. Monitoring of methane generated by landfills is achieved by setting up gas wells on the waste mass and controlled through the well head. Using real-time data from systems such as meteorological and pump stations, AI directly adjusts well heads. LoCI is designed to maximize methane capture and reduce landfill emissions by providing real-time data. AI analyses sensor data to identify trends and anomalies to provide an early warning of leaks. Machine learning algorithms assist in sorting recyclable materials from waste, thereby reducing the volume of waste ending up in landfills.

2.6. *Waste monitoring, iot and blockchain integration*

Sensors assist in identifying the sources and the amount of waste generated and analyzes the effectiveness of the waste management strategies. Real-time monitoring is essential for adaptive waste management. Wireless sensor networks provide continuous data on waste quantity, composition and system performance. When combined with AI analytics, these data enable evidence-based decision-making and performance evaluation. Blockchain technology further strengthens waste traceability by securely recording waste flows from generation to final disposal. This enhances transparency, regulatory compliance and public trust, particularly for hazardous and e-waste streams (Kouhizadeh et al., 2019).

3. Challenges and Limitations

Despite AI's immense potential in revolutionizing waste management practices, several challenges and limitations need to be overcome for its successful implementation. The training and accuracy of AI algorithms are heavily dependent upon large and heterogeneous datasets. AI solutions can be hindered by a lack of data integration and interoperability across different stakeholders in the waste management ecosystem. The data collection and monitoring systems must be reliable and robust to feed accurate, high-quality data to AI algorithms. Conventional waste management data showcases a lack of consistency, fragmentation and incomplete standardization, making it a primary challenge in AI-driven waste management. Additionally, unplanned equipment breakdowns disrupt waste collection and sorting schedules, leading to operational delays and increased maintenance costs, further impacting the overall recycling process. Data security and privacy are essential to maintain public trust and compliance with data protection regulations when AI systems access public sensitive data, such as waste generation patterns, collection routes, or user behaviour. Personal information, such as household waste generation data, is collected and stored to be used by AI systems, raising privacy concerns regarding data ownership. Incorporating IoT devices and sensor networks into waste management systems increases the risk of cyberattacks and data leakage. Large datasets and complex algorithms are tasked with AI systems through specialized hardware, software and computing resources. In terms of cost-effectiveness and scalability, AI integration into the conventional waste management system poses challenges. Technologies such as cloud computing and edge computing are cost-effective alternatives for employing AI algorithms. Decision-making processes based on AI algorithms may introduce unintentional biases, yielding frequent unintended outcomes. This issue is particularly relevant in the waste management sector, where it is vital to allocate resources and treat communities equitably. AI-based systems require transparency and responsibility to reduce biases.

4. Conclusion

Incorporating AI into waste management represents an innovative solution to tackle the global issue of waste management. Machine learning, computer vision and data analytics are the AI technologies utilized to optimize the collection, sorting, recycling and disposal of waste, thereby promoting the circular economy and benefiting both the environment and society. Comprehensive regulatory frameworks and standards must be ensured for the safe deployment of AI in waste management, while guiding its future development and application.

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