# Harnessing Artificial Intelligence for Circular Waste Systems and Climate Resilience

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**Abstract**
Climate change is widely recognized as one of the most critical global challenges, directly influenced by human activities, particularly the increasing generation and improper management of solid waste. The growing volume of municipal and industrial waste, especially in developing countries, contributes significantly to the emission of greenhouse gases such as carbon dioxide and methane, thereby threatening environmental sustainability. This issue not only exacerbates pollution across air, soil, and water resources but also intensifies public health risks and accelerates climate change impacts. Consequently, effective and sustainable waste management has emerged as a key strategy for mitigating greenhouse gas emissions. This study explores the role of artificial intelligence (AI) in enhancing waste management systems and reducing the environmental and climatic impacts associated with waste generation. Intelligent algorithms have the capability to predict waste generation trends, optimize transportation routes, automate material sorting, and evaluate climate-related policies, all of which contribute to reducing emissions and energy consumption. AI systems have achieved prediction accuracies of up to 98.5% in specific applications, such as monitoring bin fill levels. So, machine learning-based predictive models can improve the timing and efficiency of waste collection, thereby decreasing fuel use and pollutant release. The findings indicate that integrating advanced AI technologies with environmental management approaches offers a robust pathway for addressing climate challenges. Such integration can significantly support sustainable development goals by lowering the carbon footprint, improving resource efficiency, and strengthening adaptive capacity to climate change.

**Keywords:** Artificial intelligence, Global warming, Green technology, Greenhouse gas mitigation, Intelligent algorithms, Sustainable development, Waste management

## Introduction

The world is currently facing two deeply interconnected crises: the rapid escalation of waste generation and the intensification of climate change. Accelerated urbanization, population growth, and global economic expansion have led to an unprecedented surge in municipal solid waste, reaching 2.01 billion tonnes in 2016 and projected to rise to 3.4 billion tonnes by 2050. A substantial share, approximately 33%, of this waste is inadequately managed and ends up in uncontrolled or illegal dumpsites, resulting in air, water, and soil pollution, habitat degradation, biodiversity loss, and significant threats to public health. Hazardous waste streams further compromise air quality and soil integrity, while toxic leachates from landfills infiltrate groundwater, increasing the risks of cancer, childhood mortality, and infectious and chronic diseases. These challenges are compounded by the inability of existing waste management systems to cope with the growing volume of waste on a global scale. Crucially, the waste crisis cannot be separated from the climate crisis; in fact, it is one of its major accelerators. Every stage of the waste lifecycle, from collection and transportation to final disposal, serves as a direct source of greenhouse gas emissions. The anaerobic decomposition of organic waste in poorly managed landfills produces methane, a potent greenhouse gas with a global warming potential 28–36 times higher than carbon dioxide, while incineration activities and transportation contribute substantial emissions of $CO_2$ and nitrous oxide. This direct linkage underscores the need for a systemic transformation in the way waste is conceptualized: shifting from the linear model of "take–make–dispose" to a circular, zero-waste economy in which waste is treated as a recoverable and reusable resource. In response to these dual challenges, artificial intelligence (AI) and machine learning (ML) have emerged as key enablers offering intelligent computational solutions for sustainable waste management. By analyzing large-scale data and predicting waste generation patterns, AI can optimize production processes and facilitate waste reduction at the source. Throughout the waste value chain, AI plays a transformative role: in collection (route optimization), sorting (automated material recognition using computer vision), recycling (quality control and precise material separation), and sanitary disposal (prediction of methane generation and leachate formation). In various industrial sectors, AI-driven ML algorithms and real-time analytics substantially reduce energy consumption and waste generation, significantly enhancing the efficiency of management systems. Recent studies demonstrate that AI technologies not only enhance operational performance but also directly contribute to climate mitigation. Synthesizing findings from recent research allows for the development of a comprehensive and cross-disciplinary framework on the applications of AI in waste management and climate mitigation. Yevle and Mann (2025) categorized machine learning methods—supervised, unsupervised, and reinforcement learning into a structured framework for evaluating model effectiveness and guiding future research. This framework serves as a conceptual foundation for more applied studies, such as those by Ahmed et al. (2025), who integrated AI, IoT, and evolutionary algorithms to optimize waste collection and recycling systems, emphasizing the role of smart bins and performance indicators in operationalizing the circular economy. Similarly, Bianchi and Putro (2024) utilized CNN and LSTM models to demonstrate AI's capacity for real-time air quality monitoring and environmental assessment, aligning with Wani et al. (2024), who used remote sensing imagery for enhanced monitoring of landfills and contaminated zones. For greenhouse gas prediction, Jahan et al. (2024) applied ML models to estimate methane production in landfills, while Amar et al. (2024) employed a hybrid ANN–GA framework for comprehensive GHG forecasting. Alprol et al. (2024) further showed that integrating IoT and AI enables automation of water quality monitoring and treatment systems. Finally, Jones et al. (2024) emphasized that although these technologies hold substantial transformative potential for waste management and climate mitigation, their sustainable and equitable implementation requires aligning technological innovations with supportive infrastructure and policy frameworks connecting technical insights to broader socio-technical and policy-driven systems. Despite the growing number of domain-specific studies, a significant knowledge gap remains: no comprehensive review has yet examined the role of AI across the entire waste management lifecycle from source reduction to final disposal within an integrated, quantitative, and climate-centered framework. Most existing studies focus on isolated stages (e.g., sorting only or methane prediction only) without connecting them to system-level climate mitigation goals or circular economy transitions. Additionally, critical challenges such as poor data quality, the opacity of black-box models, inequality in technological access in low-income regions, and disconnects between policy and technology remain insufficiently explored. These gaps hinder the translation of technical solutions into scalable global strategies for climate action. Therefore, the objective of this systematic review is to construct a comprehensive, data-driven framework for employing artificial intelligence as a "smart, green, and clean" foundation for sustainable waste management and climate change mitigation. Integrating technical, environmental, and policy perspectives, this study seeks to address three key research questions:

1. How can AI be effectively integrated across the full waste management cycle from source reduction to final disposal in a coherent and applicable manner?
2. To what extent can AI-driven optimization reduce greenhouse gas emissions, particularly methane and carbon dioxide, across waste management processes?
3. What technical, institutional, and ethical barriers hinder the scalable and equitable deployment of AI-based waste solutions, and how can these be systematically overcome?

By answering these questions, this review not only synthesizes recent advancements but also introduces a multidimensional evaluation framework that supports the transition from fragmented, single-point solutions to intelligent, sustainable, and climate-resilient waste management systems, providing a scientific basis for developing global environmental policies, green technologies, and circular economy strategies.

## Materials and Methods

This study is designed as a systematic, library-based, and descriptive–analytical review. To examine the conceptual structure of research related to the application of artificial intelligence in waste management for climate change mitigation, bibliometric visualization and analysis were performed using the VOSviewer software (version 1.6.20). Scientific articles were retrieved from the ScienceDirect database. The search strategy employed a combination of the following keywords: *Artificial Intelligence, Waste Management, Climate Change, GHG Emissions, Recycling,* and *Environmental Sustainability*. The search timeframe covered the years 2022 to 2026, including both published articles and articles available as early-access or in-press publications. A total of 550 documents, including original research papers and review studies, were identified, which were screened following duplicate removal and relevance assessment. After title/abstract screening and full-text evaluation, 87 studies met the inclusion criteria and were retained for qualitative analysis. Using the co-occurrence analysis technique, VOSviewer automatically extracted and clustered 71 high-frequency keywords from the dataset. The analytical process was based on the eight visual and numerical outputs generated by the software, including keyword co-occurrence networks, density maps, citation networks, and thematic clusters. The final results were visualized as a network map illustrating the relationships, semantic linkages, and thematic clusters among the extracted keywords, providing insight into dominant research themes, emerging trends, and interdisciplinary connections within the field.

## Results and Discussion

### Visualization and Analysis of the Reviewed Studies

Figure 1 illustrates the intensity, distribution, and interconnections of research conducted across various domains, including waste management, sustainable development, climate change, deep learning, and neural networks. Deep learning and artificial neural networks appear as the core computational foundations of artificial intelligence within this research landscape. The visualization also highlights the strong linkage between artificial intelligence and several advanced technologies such as the Internet of Things (IoT), blockchain, energy management systems, and smart agriculture. These interrelated clusters demonstrate that AI functions as an enabling technology capable of integrating with diverse digital and environmental innovations to generate comprehensive, data-driven, and intelligent solutions. Overall, the network map underscores the pivotal role of artificial intelligence in accelerating progress toward sustainable development goals, enhancing environmental protection, and mitigating the intensifying impacts of climate change.

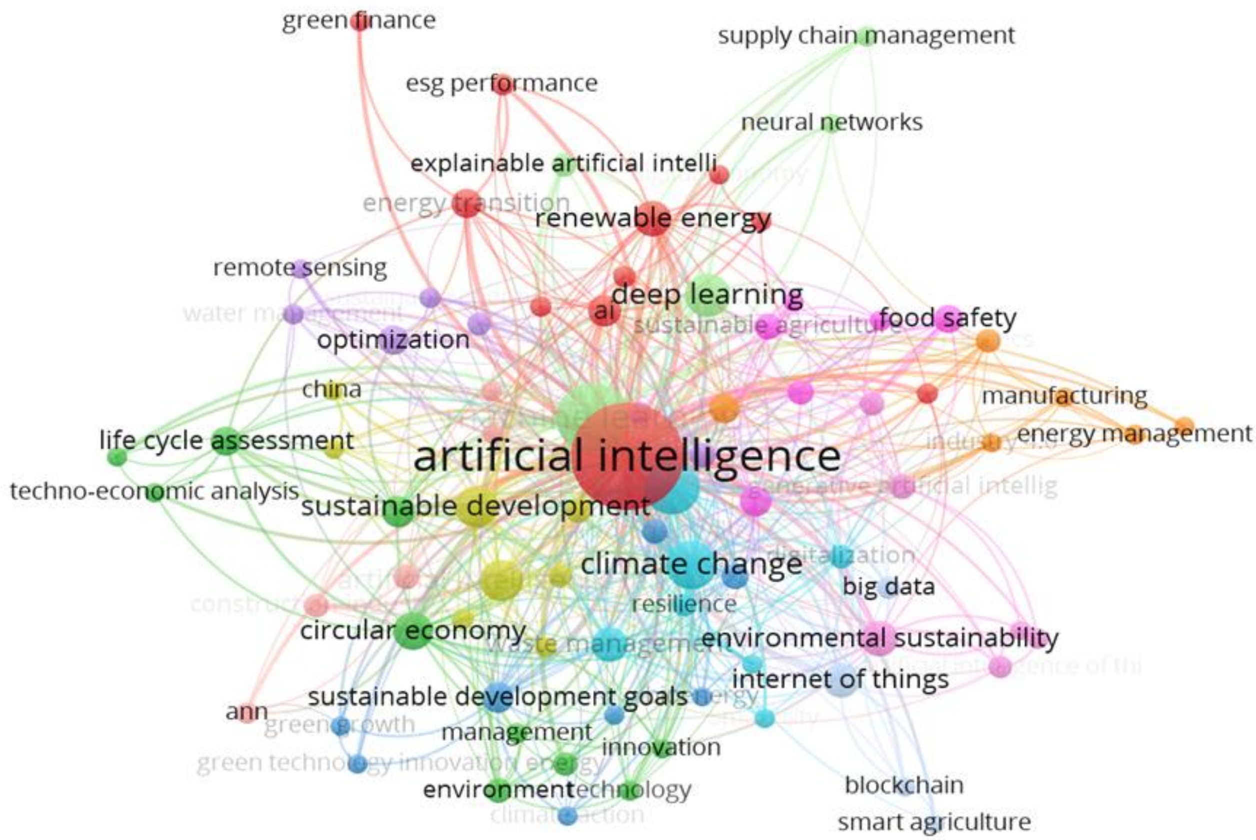


**Fig 1. Network visualization of AI, waste management, climate change, and sustainable development using VOSviewer**

As depicted in Figure 1, the application of advanced technologies, particularly artificial intelligence (AI), offers a robust approach to mitigating the detrimental impacts of waste streams on climate change. The escalating generation of solid waste and its significant contribution to greenhouse gas emissions underscore the necessity for a paradigm shift from conventional waste management strategies. Leveraging AI-driven solutions enables the optimization of waste collection, sorting, and treatment processes, thereby reducing environmental burdens and enhancing resource efficiency. Moreover, the integration of AI into waste management frameworks fosters urban resilience, improves adaptive capacity against climate-induced stressors, and contributes to sustainable urban development by minimizing pollution and promoting circular resource utilization.

**Environmental/Health Impacts**

Figure 2 depicts the comprehensive and interconnected impacts of waste on environmental systems and public health. The visualization emphasizes the linkages between air, water, and soil contamination, greenhouse gas emissions, climate change, and global warming, highlighting the systemic and multidimensional nature of waste-related hazards. This representation underscores the cascading effects of improper waste management on ecosystem integrity and human well-being, illustrating the urgent need for integrated waste management strategies and climate-sensitive interventions.

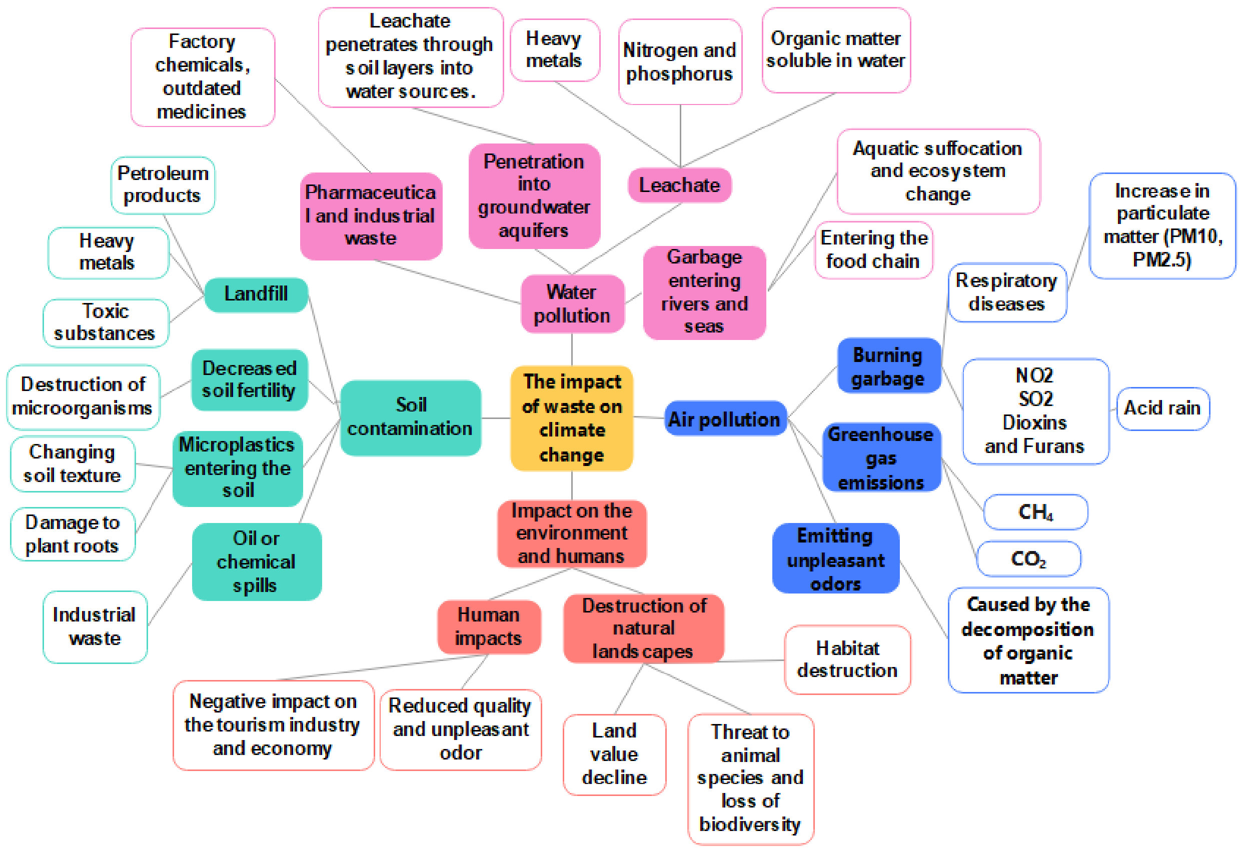


**Fig 2. Impacts of Waste on the Environment and Human Health (Vishwakarma et al., 2025)**

Improper waste management has emerged as one of the most critical environmental threats in the contemporary world. Rapid population growth, urbanization, and consumerist culture have driven waste generation to unprecedented levels. According to World Bank projections, global municipal solid waste is expected to exceed 3.8 billion tons annually by 2050. This situation is particularly acute in developing countries, where insufficient infrastructure and inadequate regulatory frameworks exacerbate environmental crises, leading to air, water, and soil pollution (Jorge, 2025). Municipal, industrial, agricultural, and electronic wastes are major sources of greenhouse gases such as methane, carbon dioxide, and nitrous oxide. Methane, produced from the anaerobic decomposition of organic waste in landfills, possesses a high global warming potential and can exert up to 28 times the warming effect of carbon dioxide, playing a significant role in accelerating global warming (Castellani, 2025; Odejobi et al., 2024). Furthermore, the incineration of waste, particularly plastics, results in the emission of hazardous compounds such as dioxins and sulfur dioxide, which not only impact the climate but also contribute to severe air pollution and a range of human health issues, including respiratory diseases, cancers, and neurological disorders (Dey et al., 2024). Uncontrolled landfilling also produces hazardous leachates containing heavy metals and toxic chemical compounds. These leachates can contaminate both surface and groundwater resources, damaging aquatic ecosystems and posing risks to human health and other living organisms. The bioaccumulation of heavy metals in aquatic organisms or crops can transfer through the food chain to humans, representing a long-term threat to food security (Saxena, 2025). Regarding soil, the infiltration of pollutants from waste can reduce fertility, degrade physical and chemical soil structure, and disrupt essential biogeochemical cycles, such as nitrogen and carbon cycles. Ultimately, proper waste management, including source separation, recycling, the application of clean technologies, and leachate treatment, plays a pivotal role in environmental protection and greenhouse gas reduction.

**Quantifiable Climate Feedback Mechanisms**

Waste and climate change share a direct and significant interrelationship, which has garnered increasing attention from researchers and environmental policymakers in recent years. Municipal, industrial, and agricultural wastes, when improperly managed, can become major sources of greenhouse gas (GHG) emissions and contributors to global warming. The production and improper disposal of waste, particularly organic and plastic materials, are key drivers of climate change. Anaerobic decomposition of organic waste in landfills generates methane, a potent greenhouse gas with a global warming potential approximately 28 times higher than carbon dioxide. Additionally, the incineration of waste, especially plastics, releases carbon dioxide and other harmful pollutants into the atmosphere, posing serious threats to human health and ecological systems. Waste management processes, including collection, transportation, and treatment, also consume significant amounts of energy; reliance on fossil fuels for these operations further exacerbates environmental pollution. Moreover, the lack of adequate infrastructure for waste separation and recycling leads to resource wastage and increased volumes of non-recyclable waste, imposing an additional environmental burden. Conversely, sustainable and properly managed waste systems can substantially mitigate climate change impacts. Employing advanced technologies in recycling, such as composting of organic waste, source separation, waste-to-energy conversion, and AI-driven optimization, contributes to reducing GHG emissions, controlling global warming, and enhancing climate regulation. In summary, waste is an integral component of the climate change cycle, directly influencing the Earth's climatic conditions. Effective public awareness, community engagement, and intelligent waste management can help steer this cycle toward a sustainable and resilient future (Wei et al., 2024).

**Strategic and Technological Waste Management**

A strategic approach to integrated waste management, emphasizing recycling and reuse, can play a critical role in mitigating greenhouse gas emissions (Pottinger et al., 2024). Advanced technologies in recycling, waste-to-energy (WTE), composting, and biological treatment of organic waste constitute effective solutions for controlling the environmental impacts of waste. Conversely, poor waste management leading to leachate generation and the release of toxic chemical compounds results in contamination of surface and groundwater, soil degradation, and threats to biodiversity. This is particularly consequential in densely populated urban areas, with direct implications for public health and food security. Sustainable and integrated waste management practices, including source separation, recycling, composting of organic materials, and the application of WTE technologies, not only reduce landfill-bound waste but also prevent the emission of greenhouse gases contributing to global warming. These processes alleviate pressure on primary resources, reduce the need for raw material extraction and processing, and directly lower energy consumption and pollutant emissions. Moreover, smart and technology-driven waste management, particularly through AI and the Internet of Things (IoT), plays a practical and active role in advancing a circular economy and mitigating climate change impacts. This approach represents not only an environmental intervention but also a macro-level climate and economic strategy aligned with sustainable development goals. Additionally, robust waste management infrastructure and strict environmental regulations are essential prerequisites for minimizing the adverse effects of waste on the global climate (Huang et al., 2024).

## Application of Artificial Intelligence in Waste Management

Artificial intelligence (AI) represents a promising tool in modern waste management. Waste management is one of the most pressing challenges for both developed and developing countries, encompassing all stages from waste generation to collection, transportation, and final disposal. Consequently, employing advanced technologies such as AI is essential to optimize these processes. The rapidly increasing volume and compositional diversity of waste, along with their environmental and economic implications, underscore the need for precise, intelligent, and efficient management solutions. AI, with its advanced algorithms and predictive tools, has the potential to fundamentally transform waste management, enabling optimized resource allocation, predictive maintenance, route optimization, automated sorting, and overall system efficiency improvements.

**Table 1. Studies on the Application of Artificial Intelligence in Waste Management**

| AI Application | Technology and Model | Application Description | References |
|---|---|---|---|
| Chemical Recycling | Support Vector Machine (SVM) | Optimization of reaction conditions for separating complex compounds | Babaei et al. (2024) |
| E-Waste Recycling | Machine Learning (ML) | Identification of valuable components, such as rare metals, from devices | Yang et al., (2024) |
| Urban Planning | Demographic and Environmental Data Analysis | Determining locations of recycling stations and resource allocation | Vadisetty & Polamarasetti (2024) |
| Transportation Route Optimization | Genetic Algorithm (GA), GIS | Designing cost-effective, fast, and low-pollution routes | Pham et al., (2024) |
| Marine Pollution Monitoring | YOLO, RCNN | Detection of marine waste patches in satellite images | Lakhouit (2025) |
| Waste Generation Pattern Prediction | Artificial Neural Networks (ANN), Decision Trees (DT) | Predicting patterns to optimize collection and resource allocation | Alprol et al., (2024) |
| Greenhouse Gas Estimation | ANN, SVM | Predicting methane production in landfills | Alsabt et al. (2024) |
| Intelligent Waste Sorting | Machine Vision, Deep Learning | Identification and classification of waste based on material, color, and shape | Che et al., (2024) |
| Illegal Waste Disposal Detection | Face and Pattern Recognition | Identifying violators using CCTV images | Opanasenko et al. (2024) |

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|---|---|---|---|
| Recycling Facilities | Digital Twin | Predicting equipment failures and optimizing performance | Vadisetty & Polamarasetti (2024) |
| Smart Composting | Adaptive Control, Real-time Data Analysis | Improving compost quality through environmental monitoring | Altieri et al. (2024) |
| Crisis Management | Reinforcement Learning and System Dynamics | Predicting waste volume during crises and rapid cleanup | Alsabt et al. (2024) |
| Citizen Engagement | Supervised Learning, Clustering | Reward systems and fraud detection | Adanma & Ogunbiyi, (2024) |

Table 1 provides a comprehensive overview of the diverse applications of artificial intelligence (AI) in the field of waste management, highlighting both technological approaches and practical objectives. The table demonstrates how various AI models, including Support Vector Machines (SVM), Artificial Neural Networks (ANN), deep learning, and machine vision, are leveraged to optimize critical processes such as chemical recycling, e-waste sorting, transportation route planning, greenhouse gas emission prediction, and smart composting. Notably, AI facilitates enhanced precision in identifying and classifying waste streams, improving efficiency in collection and recycling operations, and minimizing human intervention in hazardous or labor-intensive tasks. Furthermore, the integration of advanced optimization algorithms, digital twins, and real-time data analysis illustrates how AI supports predictive maintenance, operational efficiency, and resource allocation in both municipal and industrial waste management contexts.

The table also underscores the role of AI in promoting environmental sustainability: predictive models for greenhouse gas emissions and waste generation patterns enable proactive mitigation strategies, while intelligent sorting and monitoring systems reduce landfill dependence and enhance recycling rates. Additionally, AI-driven citizen engagement systems and reinforcement learning applications in crisis scenarios highlight the potential of these technologies to support behavioral interventions, community participation, and rapid response to environmental challenges. Overall, Table 1 reflects a clear trend toward leveraging AI not only as a tool for operational optimization but also as a strategic instrument for sustainable, data-driven, and climate-conscious waste management.

**Artificial Intelligence in the Waste Management Cycle**

**Waste Generation Prediction**

Global municipal solid waste (MSW) generation is continuously increasing due to factors such as economic growth, population expansion, and consumer behavior. It is projected that by 2025, urban waste volumes will reach 2.2 billion tons per year. Accurate prediction of municipal waste generation is essential for planning and implementing sustainable solid waste management (SWM) strategies. Reliable forecasts provide critical data for urban environmental planning and inform effective collection, transportation, and treatment strategies—activities that often require substantial investments. However, predicting urban waste generation is a challenging task, as waste production is a complex and non-linear process influenced by multiple factors, including population growth, economic status, industrialization, tourism, and social behaviors. Consequently, artificial intelligence (AI) techniques have attracted attention as computational approaches in solid waste management. AI is capable of addressing uncertain problems, learning from historical data, and handling inherent variability. By leveraging computational systems to emulate human problem-solving methods, AI models can tackle complex issues and predict outcomes in waste management. Advanced AI algorithms and predictive analytics are increasingly employed to develop smarter and more adaptive waste management systems, optimizing resource allocation while minimizing environmental impacts.

**AI Models and Techniques**

A wide range of AI models, including statistical models, machine learning, deep learning, and fuzzy logic, are applied for waste generation prediction. AI algorithms are considered powerful predictive tools due to their ability to process input data, learn patterns, and make reliable forecasts. These techniques, which encompass machine learning and deep learning methods, can identify waste generation patterns and associated behaviors, supporting informed decision-making. Common AI systems in waste management include Artificial Neural Networks (ANNs), Support Vector Machines (SVMs) or Support Vector Regression (SVR), decision trees, linear regression, and genetic algorithms. Other techniques, such as Adaptive Neuro-Fuzzy Inference Systems (ANFIS) and knowledge-based expert systems, have also been employed. Among these models, ANNs have been most widely used for predicting waste generation, followed by SVMs. ANNs are structurally robust, fault-tolerant, and effective in capturing complex relationships in multivariable systems. More advanced deep learning models, such as Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs), particularly Long Short-Term Memory (LSTM) networks, have demonstrated substantial potential. LSTM models excel in sequence prediction and can achieve high accuracy in forecasting municipal waste generation, especially with large datasets. Gradient Boosted Regression Trees (GBRT) provide another powerful approach, often delivering better results than ANNs due to strong generalizability and easier interpretability. To enhance predictive performance, these AI models are sometimes combined with other analytical methods, such as spectral analysis, principal component analysis (PCA), or Hidden Markov Models (HMMs). These models can be applied across different forecasting horizons, including short-term (days to months), medium-term (up to 3–5 years), and long-term (several years).

**Applications and Scope**

Artificial intelligence (AI) models are widely employed to predict various characteristics of waste generation, including mass, composition, type, and rate. Such predictions enable the systematic collection, treatment, and disposal of municipal waste. Forecasting waste generation is the most common application of AI in solid waste management. These models can also predict specific waste streams, such as plastic waste, and can be applied across short-, medium-, and long-term forecasting horizons. Beyond generation rate prediction, AI applications have expanded into other critical areas of waste management. These include optimization of waste collection truck routes, management of collection networks, monitoring bin levels to prevent overflow, and identification of safe landfill sites. AI is also applied to model and enhance processes such as biogas production and leachate management. By integrating AI with technologies such as the Internet of Things (IoT), more efficient and environmentally compatible waste management systems can be developed, which contribute to emission reductions and enable the recovery of valuable resources such as clean water and energy from waste streams.

**Data and Influencing Factors**

The accuracy of AI prediction models heavily depends on the quality and scope of data used for training, which includes both historical and current waste generation patterns. Waste production is influenced by a wide array of factors, typically categorized into social, economic, and environmental domains. Key variables include population growth, economic status, industrialization, tourism, social development, and demographic details. Additional influential factors may include meteorological conditions and even building aging indices. By analyzing these complex relationships, AI models can provide more reliable and accurate predictions for different types of waste, including household, commercial, and construction waste.

**Model Performance**

The performance of AI models in waste prediction is commonly evaluated using metrics such as the coefficient of determination ($R^2$), mean squared error (MSE), mean absolute error (MAE), and root mean squared error (RMSE) (Ghochanian Haghverdi et al., 2025; Helmi et al., 2024). High $R^2$ values and low error values indicate strong predictive accuracy. For instance, Multi-Layer Perceptron Artificial Neural Networks (MLP-ANNs) have achieved $R^2$ values of 0.95 for household waste, 0.99 for commercial waste, and 0.91 for construction waste. In other studies, a combination of Partial Least Squares Regression (PLS) with Support Vector Machines (SVMs) reached an $R^2$ of 0.87, while Adaptive Neuro-Fuzzy Inference Systems (ANFIS) demonstrated the highest accuracy in predicting peak waste generation. Hybrid models such as CNN-LSTM-GBM have exhibited outstanding predictive performance, achieving an $R^2$ of 99.5% and a low MAE of 0.15. Even in specific applications such as monitoring bin fill levels, AI systems have demonstrated prediction accuracies as high as 98.5%. These results underscore the effectiveness of AI and hybrid modeling approaches in achieving reliable and precise waste management predictions.

**Challenges of Artificial Intelligence in Waste Management**

In developing countries, such as many regions in Latin America, the implementation of AI in municipal waste management faces numerous challenges that limit the full exploitation of this technology's potential. A primary issue is the low quality of data, as many municipalities still lack accurate systems for recording and storing waste-related information. Data are often collected manually, in a fragmented manner, and without standardized protocols, which reduces the accuracy of AI-based analyses. Moreover, the lack of coordination among different systems, such as GIS, environmental monitoring, and urban datasets, creates inconsistencies that hinder intelligent decision-making. Infrastructure limitations further complicate the situation, including insufficient equipment, low internet speeds, the absence of secure cloud platforms, and challenges in effectively integrating technologies such as the Internet of Things (IoT) and machine learning. Financial constraints and a shortage of skilled personnel also impede project implementation. As a result, many initiatives remain at the proposal stage or are executed with suboptimal performance. Institutional resistance to new technologies, concerns over data security, and public distrust of automated decision-making systems further slow the adoption of AI. Overall, the lack of effective communication among government agencies, technology providers, NGOs, and citizens prevents the establishment of social support and public engagement. Addressing these issues requires a multidimensional strategy combining smart policy-making, technological investment, workforce training, and public awareness campaigns (Yevle & Mann, 2025). Another critical challenge in AI model deployment is overfitting, a condition in which a model performs well on training data but poorly on new, unseen datasets. This issue can be mitigated through hybrid modeling approaches that combine multiple AI models, resulting in more robust and accurate predictions. Additionally, the processing of large volumes of data generated by sources such as IoT devices presents challenges for real-time decision-making. Despite these obstacles, AI techniques are continuously evolving, improving predictive accuracy over time. The iterative learning capability of AI enables waste management systems to progressively enhance algorithms and forecasting methods as more data are collected and processed.

**Optimization and Decision Support**

Beyond prediction, AI models provide fundamental decision support for optimizing waste management logistics. A key application is vehicle routing, where AI algorithms optimize collection schedules and routes. For instance, AI can utilize waste generation forecasts to estimate future volumes of waste and recyclable materials, and then, using Geographic Information Systems (GIS), optimize collection routes. Genetic algorithms (GA) are employed to identify near-optimal routes for collecting specific waste types, such as discarded electrical and electronic equipment (WEEE), from households. These optimized routes can be computed rapidly on standard computers, improving collection efficiency. Multi-criteria models can further enhance decision-making by using fuzzy logic to balance factors such as route length and resident satisfaction, measured by collection delays. One of the most important roles of AI is intelligent waste sorting at recycling centers. Systems equipped with advanced cameras, computer vision, and deep learning algorithms can identify and categorize waste based on material, color, and shape (Che et al., 2024). Robotic arms can separate plastics, glass, metals, and organic materials, reducing human exposure, increasing sorting accuracy, and improving recycling efficiency. AI also analyzes spatial and temporal data on urban waste generation to identify patterns and forecast waste volumes using models such as Artificial Neural Networks (ANN) and Decision Trees (DT). These predictions help municipal managers optimize collection timing, workforce allocation, and equipment deployment (Alprol et al., 2024). In waste transportation, route optimization algorithms, such as GA combined with GIS, design collection paths that consider factors like bin fill levels, traffic, and distances, resulting in faster, lower-cost, and lower-emission routes. This reduces fuel consumption and the carbon footprint of waste transport. Illegal dumping has become a serious issue in many large cities; AI can leverage facial recognition and pattern recognition algorithms on CCTV footage to identify violators and prevent recurrence (Pham et al., 2024; Opanasenko et al., 2024). In electronic waste (E-waste) recycling, machine learning (ML) systems can identify valuable components such as rare metals, gold, or silver from old electronics and separate them for recycling with high precision (Yang et al., 2024). In chemical recycling processes, models like Support Vector Machines (SVM) determine optimal reaction conditions to separate complex compounds (Babaei et al., 2024). At a larger scale, AI analyzes demographic, economic, and environmental data to support urban policymakers in strategic planning. For example, regional data analysis can identify areas in need of recycling stations and optimize resource allocation. Advanced recycling plants employ digital twins—virtual models of physical equipment and processes—to simulate operations, predict equipment failures, optimize performance, and reduce production downtime (Vadisetty & Polamarasetti, 2024). In crisis scenarios such as earthquakes or storms, reinforcement learning and system dynamics models predict waste volumes generated and support rapid cleanup planning. AI-based prediction models, such as ANN or SVM, can also estimate greenhouse gas emissions, including methane, at landfill sites and suggest mitigation strategies (Alsabt et al., 2024). Smart composting systems use sensors, adaptive control algorithms, and real-time data analysis to monitor environmental conditions such as temperature, humidity, and oxygen levels, thereby improving compost quality (Altieri et al., 2024). To enhance citizen participation, behavioral scoring systems use supervised learning and clustering algorithms to reward individuals for proper waste separation and detect fraudulent or false reports (Adanma & Ogunbiyi, 2024). Globally, AI analyzes satellite imagery to identify marine debris patches, employing object detection models such as YOLO (You Only Look Once) and RCNN for effective ocean pollution monitoring. In mining and construction industries, ANN-GA models optimize fuel consumption of heavy machinery by assessing load, slope, path resistance, and speed, thereby reducing costs and emissions (Lakhouit, 2025). AI has rapidly emerged as a transformative tool in waste management worldwide, with applications spanning collection, sorting, recycling, waste generation forecasting, and pollution monitoring. Leading countries such as the Netherlands, Germany, and Sweden have pioneered AI use in this sector. In the Netherlands and Germany, robotic systems equipped with computer vision are deployed for automated separation of recyclables (Dindorf & Wos, 2024). In Finland, systems like Enevo employ machine learning algorithms to predict bin fill levels and design efficient collection routes (Kwilinski et al., 2024). In the United States, companies such as Rubicon Global utilize AI-based technologies for intelligent waste tracking and management (Nwokediegwu et al., 2024). San Francisco employs smart imaging systems for automatic waste recognition and sorting (Yap et al., 2024). Research institutions, such as MIT, have developed models for predicting urban waste generation patterns using advanced algorithms and city datasets. In China, the Shanghai municipality uses AI systems to monitor citizens' waste separation behavior with smart cameras and identify violations. AI-equipped robots are also deployed in Chinese recycling plants for e-waste separation (Mukhamedjanova et al., 2025; Xiong et al., 2025). In developing countries such as India, AI is applied in urban projects to optimize recycling systems, educate citizens, and identify high-accumulation waste hotspots. Startups in cities like Bangalore and Pune use AI and IoT to monitor pollution and improve recycling performance (Adeoba et al., 2025; Brahim & Lahiani, 2025). In the Middle East, including the UAE and Saudi Arabia, AI forms an integral part of smart city initiatives, such as Dubai and the NEOM project, designed for smart waste cycle management, landfill avoidance, and progression toward a circular economy (Qurashi et al., 2025). Even in African countries such as Kenya and Nigeria, AI is increasingly applied in municipal waste management for environmental data analysis, identifying high-risk locations, and designing optimal waste collection routes (Nwokediegwu et al., 2024).

**Application of Artificial Intelligence in Greenhouse Gas (GHG) Estimation**

Reducing greenhouse gas (GHG) emissions and air pollution has become a central objective of environmental policies, particularly in industrialized countries such as China. As the world's largest $CO_2$ emitter, China has made significant progress by implementing stringent energy-saving policies, clean energy production projects, and using assessment models such as GAINS and AIM/Local. However, certain sectors, including transportation, have received relatively less attention. Bayesian Belief Network (BBN) models, energy system models like MARKAL, and advanced statistical tools provide more precise analysis of GHG emissions. In agriculture, advanced models such as DNDC and DayCent are increasingly applied to estimate the impacts of different cultivation practices and climatic conditions on emissions. In the waste management sector, substituting recycled materials for virgin raw materials plays a critical role in reducing fossil fuel consumption, GHG emissions, and overall energy use. In developing countries such as Brazil, initiatives for recyclable waste collection, public awareness campaigns, and supportive policies have been implemented to promote sustainable waste management (Santos et al., 2024). AI has shown considerable potential in optimizing wastewater treatment processes and predicting water quality parameters, including BOD, COD, and TSS, while enhancing energy efficiency.

Techniques such as Artificial Neural Networks (ANN), Fuzzy Logic (FL), Genetic Algorithms (GA), and Support Vector Machines (SVM) are employed to develop accurate predictive models and control complex processes. Hybrid models like ARIMA-ORELM, ANFIS-GFO, and reinforcement learning (RL) algorithms have been developed for real-time management and smart automation of treatment facilities. Additionally, emerging technologies such as IoT-based monitoring systems, unmanned surface vehicles (USVs), and wireless sensor networks (WSNs) enable continuous water quality monitoring even in hard-to-access areas. Overall, integrating AI not only reduces operational costs and energy consumption in treatment processes but also supports optimized decision-making and enhances environmental sustainability (Naturinda et al., 2025).

**Predictive Modeling for Greenhouse Gas Emissions, Climate Forecasting, and Environmental Monitoring**

Artificial intelligence (AI) has emerged as a transformative tool in addressing critical environmental challenges, particularly in the management of greenhouse gas (GHG) emissions, climate forecasting, and broader environmental monitoring. AI models are widely employed to estimate emissions from diverse sources, including industrial activities, energy systems, and waste management processes, with hybrid deep learning architectures such as CNN-LSTM achieving prediction accuracies as high as 99.5% ($R^2 = 0.995$). Beyond emissions forecasting, AI techniques, including neural networks, fuzzy logic, and machine learning, enable accurate prediction of environmental quality parameters such as ozone concentration, pH, dissolved oxygen, and temperature, while also supporting early warning systems for extreme weather events such as tornadoes and large-scale storms. In waste management, AI facilitates optimization of collection routes, intelligent sorting of recyclables using computer vision and robotic arms, prediction of waste generation patterns, and estimation of GHG emissions from landfills, thereby minimizing environmental impacts and operational costs. Moreover, AI-driven frameworks support the development of mitigation and adaptation strategies by identifying emission reduction opportunities, monitoring deforestation, designing low-carbon transportation systems, and integrating IoT and smart sensor networks to enhance real-time monitoring and decision-making. Collectively, these applications underscore AI's potential to optimize resource allocation, reduce energy consumption, improve environmental quality, and contribute significantly to global sustainability efforts, with estimates suggesting it could reduce worldwide GHG emissions by up to 4%.

**Challenges of Artificial Intelligence in Global Warming**

The application of artificial intelligence (AI) in combating global warming and promoting sustainability is widely recognized due to its predictive and optimization capabilities. However, AI is often described as a "double-edged sword" because of significant inherent challenges and risks that, if not properly managed, could exacerbate environmental crises.

**Dual Nature and Potential to Amplify Negative Effects**

A primary challenge is the intrinsic duality of AI: on one hand, it serves as a powerful tool for advancing Sustainable Development Goals (SDGs), while on the other hand, it introduces multifaceted complexities and risks. The very capabilities that allow AI to support sustainability, if applied unethically or destructively, can amplify negative impacts, including accelerated global warming, pollution, excessive resource consumption, and unsustainable production practices.

Therefore, careful monitoring and assessment of unintended consequences, alongside strategies to mitigate adverse outcomes, are essential.

**Environmental Footprint from Electronic Waste and Hardware**

AI systems heavily rely on physical infrastructures such as sensors, servers, and connected devices, which impose a significant environmental footprint throughout their lifecycle. The rapid development of AI technologies has substantially increased electronic waste volumes, making proper management a critical environmental priority. Electronic waste contains hazardous chemicals, including flame retardants like TBBPA, PBB, and PBDE in plastic components, and polyvinyl chloride in cable insulation. These substances are highly persistent, bioaccumulative, and toxic to humans and ecosystems. Improper disposal, particularly open-air incineration, releases harmful pollutants into the air, soil, and water. Human exposure can result in serious health consequences, including cancer, congenital abnormalities, reproductive issues, developmental delays, and immune system disruption. Despite growing awareness of these risks, there is an urgent need for comprehensive strategies, including national and international roadmaps for sustainable electronic waste management, which should align environmental protection with public health objectives and global climate action initiatives.

**Systemic and Governance Barriers to Effective Implementation of Artificial Intelligence**

Even the most advanced AI solutions, such as intelligent routing algorithms for waste collection or real-time monitoring systems for waste bins, face significant non-technical barriers that limit their real-world impact on climate action.

**Regulatory and Market Pressure Deficiencies**

The adoption of AI in critical areas such as smart waste management is often hindered by the absence of stringent regulatory frameworks and weak market incentives. Without external pressure or well-defined legal mandates, the implementation of these technologies remains fragmented and unsustainable. Regulatory gaps also hinder the standardization of data collection and sharing, which is essential for AI systems to operate efficiently and make accurate predictions. In addition, the lack of clear guidelines regarding environmental responsibility, accountability, and performance evaluation further constrains the potential of AI to contribute effectively to climate mitigation goals.

**Lack of Public Awareness and Societal Engagement**

A fundamental barrier lies in the limited environmental literacy among the general population and the underdeveloped culture of environmental stewardship. Transitioning toward circular economy models requires collective behavioral changes that AI alone cannot enforce. Success depends not only on technological deployment but also on public engagement, education, and behavioral incentives. Without widespread awareness and societal acceptance, AI interventions risk low adoption rates or unintended consequences, such as reinforcing existing inequalities in waste management access.

**Investment and Institutional Coordination**

Scaling AI for sustainability requires significant financial investment, long-term commitment, and multi-stakeholder coordination. Implementing AI technologies aligned with sustainable development objectives entails upfront costs for infrastructure, software, sensor deployment, and workforce training. Achieving global environmental goals necessitates robust collaboration among governments, private sector entities, local communities, labor forces, industries, and academic institutions. Institutional fragmentation, bureaucratic inertia, and misaligned incentives can further delay or dilute the effectiveness of AI deployment.

**Data Governance and Standardization Challenges**

AI systems rely heavily on accurate, high-resolution data. Fragmented data sources, inconsistent reporting standards, and the lack of interoperable platforms reduce the predictive accuracy and decision-support capabilities of AI solutions. Establishing standardized data protocols, transparent governance mechanisms, and secure data-sharing frameworks is crucial for unlocking the full potential of AI in climate and waste management strategies.

**Equity and Inclusion Considerations**

Finally, effective AI implementation must account for equity and inclusion. Without mechanisms to ensure equitable access, AI-driven systems risk privileging certain communities over others, potentially exacerbating social and environmental inequalities. Policies should explicitly address how AI deployment affects different socio-economic groups and ensure that benefits such as improved waste collection, energy recovery, or environmental monitoring are distributed fairly across populations. While AI holds immense potential for enhancing climate action and sustainable waste management, its impact will remain limited unless systemic, governance, and societal barriers are strategically addressed through policy frameworks, public engagement, institutional collaboration, and robust data governance. Only through an integrated approach can AI transition from a promising technology to a transformative tool for global sustainability.

**Future Research Perspectives**

The future outlook for waste management leveraging artificial intelligence (AI) is promising, offering the potential for transformative impacts in reducing environmental effects and addressing climate change and global warming. AI can optimize waste collection, segregation, recycling, and disposal processes by analyzing complex datasets, while efficiently preventing the release of harmful and toxic pollutants from landfill and incineration activities. One of the most significant applications of AI in this domain is the continuous and intelligent monitoring of waste during collection and recycling processes. By integrating Internet of Things (IoT) technologies with machine learning algorithms, AI systems can identify waste generation patterns and predict optimal conditions for recycling. These systems can also automatically detect the composition of waste and guide it toward appropriate recycling or proper disposal pathways, thereby reducing landfill waste and limiting methane and carbon dioxide emissions. Furthermore, AI can play a pivotal role in designing and developing predictive models for estimating municipal and industrial waste generation. Such models can assist policymakers in making data-driven and intelligent decisions regarding resource management and carbon footprint reduction. The use of robots equipped with machine vision for waste sorting in recycling facilities represents another practical and efficient application of AI, contributing to pollution reduction caused by improper waste management. Beyond municipal and recycling operations, AI can support industrial and mining sectors by developing smart monitoring systems for waste generation, analyzing product life cycles, identifying industrial waste pollution sources, and offering solutions to minimize waste production during manufacturing processes. Additionally, AI-enabled digital platforms can enhance public participation in waste reduction, promote source-separation practices, and increase environmental awareness regarding the consequences of waste. AI can also address challenges such as access to accurate data, privacy protection, operational costs, and workforce training, providing comprehensive solutions to support sustainable waste management. With effective collaboration between governments, the private sector, local communities, and civic organizations, the full potential of advanced AI technologies can be harnessed to reduce pollution, mitigate climate change, and prevent global warming. So, AI has the capability to establish intelligent infrastructure and data-driven decision-making frameworks, making it a key tool for efficient, sustainable, and optimized waste management. By minimizing waste, reducing emissions, and supporting climate mitigation strategies, AI can contribute significantly to combating global warming and promoting environmental sustainability.

## Conclusion

This systematic review highlights the transformative potential of AI in advancing sustainable waste management and mitigating climate change. The integration of AI across the entire waste lifecycle, from generation prediction and collection optimization to sorting, recycling, and final disposal, demonstrates significant opportunities for reducing greenhouse gas emissions, enhancing resource efficiency, and promoting circular economy principles. AI-driven technologies, including machine learning, deep learning, computer vision, and IoT-enabled platforms, enable real-time monitoring, predictive modeling, and intelligent decision-making, thereby optimizing operational efficiency while minimizing environmental impacts. Despite these advances, the deployment of AI in waste management faces multifaceted challenges, including data quality limitations, infrastructural constraints, high implementation costs, regulatory gaps, and equity concerns. Moreover, the environmental footprint of AI itself through electronic waste and energy-intensive hardware must be carefully managed to avoid unintended negative consequences. Addressing these systemic, technical, and societal barriers requires an integrated approach that combines robust governance, standardized data protocols, multi-stakeholder collaboration, and public engagement. Looking forward, future research should focus on developing hybrid AI models that enhance predictive accuracy, integrating AI with emerging technologies such as digital twins and advanced sensor networks, and designing equitable frameworks that ensure inclusive access to AI-driven waste solutions. Additionally, cross-disciplinary studies are needed to quantify the net environmental benefits of AI adoption, considering both its operational efficiency and lifecycle impacts, to guide global policy and investment decisions. In conclusion, AI represents a powerful enabler for achieving sustainable waste management, advancing circular economy goals, and mitigating climate change. When deployed responsibly and strategically, AI has the capacity to transform waste systems from reactive, linear models into proactive, intelligent, and climate-resilient infrastructures, contributing substantially to global sustainability and environmental stewardship.

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