



Smart Waste Management Framework Using Artificial Intelligence and Internet of Things with Adaptive Eco-Intelligence for Sustainable Urban Environments

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Abstract- Fast urbanization and higher population growth have drastically raised the amount of municipal solid waste generated, posing challenges for effective waste collection, resource utilization and environmental sustainability. Traditional waste management practices have been wasteful due to rigid schedules, centralized tracking, overflowing wastebins, suboptimal vehicle routes, fuel usage, and carbon emissions. This paper introduces a novel Artificial Intelligence (AI) powered smart waste management framework, named as EcoWasteNet, encompassing the Internet of Things (IoT), edge intelligence, Adaptive Eco-Cognitive Optimization (AECO), Waste Digital Twins and cloud analytics for intelligent and sustainable waste management. The proposed framework is designed to continuously gather real-time data from the smart waste bins that are fitted with fill level, weight, gas, temperature, moisture and image sensors. Edge intelligence does local data preprocessing, waste classification, contamination detection and overflow prediction to reduce the latency of communication, dependence on the cloud. The proposed algorithm, AECO, optimises waste collection dynamically by optimising fuel consumption, carbon emission, collection delay and overflow probability and maximising the recycling efficiency, vehicle utilisation and collection performance. Additionally, the Waste Digital Twin keeps a virtual representation of every smart bin in real time, tracking waste production trends, forecasting future fill levels and aiding in proactive decision making. The proposed framework is experimentally validated and shows an overall waste classification accuracy of 98.5%, overflow prediction accuracy of 97.8%, reduction in fuel consumption of 31%, reduction in carbon emissions of 34%, recycling efficiency of 96.9% and overall sustainability score of 97.6%, which outperforms the conventional IoT-based waste management approach. In the proposed EcoWasteNet framework, AI and IoT, edge computing, digital twins and adaptive optimization are the key technologies that enable the creation of a scalable, smart and environmentally friendly solution for next-generation smart cities to perform waste collection and manage resources efficiently.

Keywords : Smart Waste Management, Artificial Intelligence, Internet of Things, Edge Intelligence, Waste Digital Twin, Adaptive Eco-Cognitive Optimization, Sustainable Smart Cities, Waste Classification, Overflow Prediction, Route Optimization, Recycling Efficiency, Carbon Emission Reduction and Resource Management.



1. Introduction

As urbanization, industrialization and consumer behavior have rapidly accelerated over the years, the amount of municipal solid waste (MSW) produced has skyrocketed around the globe. The recent global estimates indicate that there is a generation of millions of tons of solid waste every day, which creates a strain on the current waste collection and disposal mechanisms. The poor management of waste can be harmful to public health, urban cleanliness and cause environmental pollution, greenhouse gas production, too much fuel usage, and poor use of natural resources. Thus, the need for smart cities and sustainable urban development for the creation of smart and sustainable waste management systems has become a critical priority.

The traditional waste management systems are based on waste collection frequency without taking into consideration the amount of waste products in the collection bins. This means that waste collection vehicles frequently need to go through partially full bins, while bins that are overfilled are left without anyone watching, which adds to the expenses of transporting waste, additional fuel usage, road congestion and carbon emissions. Moreover, manual waste bin monitoring demands a lot of manpower and is unable to provide real-time information on waste generation trends. Such restrictions impact on the efficiency of operations, and can pose a challenge in the adoption of environmentally sustainable waste management practices.

The Internet of Things (IoT) has revolutionized waste management by introducing smart waste bins that are connected and can be monitored in real-time. Fill level, weight, temperature, gas, moisture and location sensors are installed in the waste bins to continuously monitor and communicate operational data to centralized management systems via IoT. It is a real-time monitoring which is used for better collection planning, reduce the number of unnecessary trips and increase the efficiency of the operation. Most existing IoT waste management solutions, though, heavily depend on cloud computing, communication delays, bandwidth consumption, power usage and lack of scalability, when handling the huge amounts of sensor data produced on the urban scale.

Artificial Intelligence (AI) has proven to be a promising technology solution to solve these issues as it allows intelligent waste classification, overflow prediction, route optimization and decision support. Machine learning and deep learning algorithms can accurately assess sensor data and waste images to forecast the quantity of waste in the bins, waste category, contamination and future waste generation patterns. These capabilities are intelligent, which enhances the efficiency of recycling and optimizes waste collection. However, the current AI-based waste



management solutions do not support multiple tasks simultaneously, including image classification and route optimization, and sustainability metrics like fuel consumption, carbon emissions, resources used, recycling rates etc. are not taken into account.

Edge computing has recently been receiving a lot of attention for implementing a new way to process data generated by IoT devices closer to the source, thus minimizing the latency of the communication links and dependence on cloud resources. Lightweight AI models deployed at the edge can enable real-time monitoring and some decision-making at the edge and only send pertinent information to cloud servers. However, most current waste management systems based on the edge do not have systems which can optimise in a unified way the three factors of environmental protection, dynamic waste generation, intelligent vehicle scheduling and autonomous operation.

To address these challenges, a novel smart waste management framework called EcoWasteNet is introduced in this paper, which combines IoT, Edge Intelligence, Adaptive Eco-Cognitive Optimization (AECO), Waste Digital Twins and cloud analytics with a unified intelligent architecture. Smart bins are constantly monitored by multiple IoT sensors by EcoWasteNet while at the edge of the network, sensors perform local AI-based waste classification, contamination detection and overflow prediction, unlike traditional waste management. The AECO (Adaptive Eco-Cognitive Optimization) algorithm proposed dynamically optimizes waste collection, while simultaneously minimizing fuel consumption, collection delay, overflow probability, carbon emissions, maximizing recycling efficiency, vehicle utilization and operational sustainability. The Waste Digital Twin also has a real-time virtual model of each smart waste bin that allows waste generation trends to be monitored constantly, waste fills to be predicted, recycling potential to be evaluated and maintenance plans to be made proactively. The cloud analytics layer also enables extended data analytics, municipal sustainability reporting and strategic decision-making.

The proposed EcoWasteNet framework has a number of important features over current solutions. First, it integrates IoT sensing, edge intelligence, adaptive optimization, digital twin and cloud analytics in an all-in-one package. Second, the proposed AECO algorithm optimizes the operational efficiency and the environmental conservation at the same time, by adopting the multi-objective decision making approach. Third, with the Waste Digital Twin, it is possible to make predictions on waste for better waste management, such as overflow forecasting and scheduling waste collections proactively. Last but not least, edge intelligence reduces communication overheads, limits the cloud's dependence and allows for real-time decision making on large scale smart city deployments.

This paper makes a number of contributions, which are summarized as follows:



- The integration of IoT, Edge Intelligence, Waste Digital Twins, Adaptive Eco-Cognitive Optimization and cloud analytics is proposed as a novel framework, called EcoWasteNet, for intelligent and sustainable smart waste management.
- New Adaptive Eco-Cognitive Optimization (AECO) algorithm is designed for the joint optimization of waste collection routes, fuel consumption, carbon emission, vehicle utilization, waste recycling efficiency and delays in collection.
- A Waste Digital Twin model is proposed to track waste generation on an ongoing basis, forecast overflow conditions, assess the recycling capacity and enable proactive waste management.
- An intelligent edge computing strategy aims to classify waste locally, detect contamination at the edges, and predict overflows, which will minimize communication latency and cloud processing.
- The experimental assessment shows that the proposed framework can achieve a high accuracy in waste classification, high efficiency in waste recycling, high use efficiency of fuels, high sustainability performance and overall high efficiency as compared to the current IoT-based waste management systems in operation.

The following is the organization for the rest of this paper. The recent literature related to smart waste management, Artificial Intelligence, IoT, edge computing, digital twin and sustainable urban waste collection were reviewed in Section 2. Section 3 provides a proposed ecoWasteNet framework and operational architecture. The experimental evaluation and the results obtained are described and discussed in section 4. In the last section, the paper is concluded and the future research directions are given.

2. Related Works

With the advent of Artificial Intelligence (AI), the Internet of Things (IoT), edge computing and data analytics, waste management systems have been completely revolutionized into smart waste management systems. In today's waste management system, the main emphasis is placed on real-time monitoring, waste classification, optimizing waste routes, improving waste recycling, and sustainability. Although significant strides have been made, the studies conducted have more often focused on individual problems, and not on an integrated solution that can address operational efficiency, environmental sustainability and intelligent decision-making.

Studies in recent years have shown that ultrasonic, weight and environmental sensors can be installed in smart waste bins to get data on waste levels and relay the updated data to a centralized system in real time [1]. These systems are



good for collection planning, but are based on fixed scheduling algorithms that do not respond to variable waste generation patterns.

AI has been widely used to classify municipal waste by deep learning models based on waste images captured from smart bins [2]. While they are effective at classification, most of these methods are only focused on the recognition of the image and not on waste collection or any measures to enhance sustainability.

Other machine learning algorithms have been used to forecast future bin fill levels and patterns of bin waste generation based on previous sensor data [3]. While their predictive capabilities are enhanced, these models typically do not consider traffic, vehicle utilization and environmental effects in waste collection.

Cloud based IoT architectures have been proposed by some researchers for monitoring the smart waste bin in urban environment [4]. While these systems offer a centralized data management and visualization platform, they are limited in communications latency, bandwidth usage and scalability because they continuously transmit raw sensor data.

The last few years, edge computing has become an effective solution to handle the data from IoT devices, where these devices are closer to the waste collection points [5]. Local processing helps to decrease communication latency and dependency on clouds. However, many edge-based frameworks only do basic filtering of data, and do not incorporate intelligent routing or embedding the concept of sustainability into decision making.

To automatically recognize the recyclable and non-recyclable waste materials, computer vision techniques were used in smart bins [6]. The systems help to segregate wastes but in general they do not take into account the real-time scheduling of waste collection, fuel optimization, or carbon emission reduction.

To reduce the distance of waste collection and transportation costs, intelligent route optimization algorithms have been proposed that take into account the locations of bins and traffic information [7]. But most of the routing algorithms only optimize the travel distance without considering any of the overflow risk, recycling efficiency, vehicle utilization and environmental sustainability aspects.



In recent years, a new paradigm of digital twin technology has been introduced to the management of urban infrastructure, which is a virtual representation of physical assets to monitor and predict [8]. Current digital twin solutions in waste management are mostly related to the visualisation of infrastructure and monitoring of equipment and offer only a small range of support in adaptive sustainability optimisation and intelligent waste collection.

The application of deep reinforcement learning to autonomous decision-making for dynamic waste collection problems has been studied [9]. While RL-based adaptive routing methods are useful, most of them require large amounts of training data, and in some cases aim for only one objective when operating.

There are examples of introducing blockchain technology in waste management to increase transparency and traceability, and secure information sharing between players in the waste management chain [10]. While blockchain technologies can improve data security, they also come with increased computational costs and the use of energy, which can hinder their applicability in a sustainable smart city context.

Other approaches have been used to detect the condition of the smart waste bin and collection equipment during operation, applying predictive maintenance techniques [11]. These techniques are used to minimize the occurrences of unexpected equipment failures but typically do not all fit into a single framework of waste prediction, intelligent routing, and environmental issues.

To analyze large-scale waste generation patterns and provide strategic urban waste management decision-making, big data analytics has been applied [12]. Such analytical approaches are useful for municipal planners, but are not necessarily coupled with real-time IoT sensing and adaptive controls.

In recent studies, it has been pointed out that sustainability indicators like fuel consumption, recycling rate, greenhouse gas emissions and resource use are the key elements that need to be considered when measuring waste management performance [13]. Many of the current systems use these indicators only when they have finished their analyses, but do not include them in the actual optimization process.



The integration of multiple intelligent technologies has also proven to be an effective way to enhance the operational efficiency and delivery of public services in an urban environment [14] by means of AI-assisted smart city management systems. However, these concepts are seldom integrated into a single waste management architecture using IoT sensing, edge intelligence, digital twins, adaptive optimization and sustainability assessment.

Smart cities have seen promising developments in the use of intelligent urban infrastructure which is capable of integrating Artificial Intelligence, IoT, Cloud Computing, and autonomous decision-making to enable city management in a sustainable way [15]. Current solutions, however, tend to optimize individual components separately, which makes them less flexible and adaptable to the fast-changing urban context, and makes the operation more complex.

Based on the literature, it can be seen that most of the existing smart waste management systems focus on a single aspect of the waste management, for example, classification, level sensor, route planning and management, or cloud management. Very little research has been conducted on optimizing simultaneously the efficiency of waste collection, waste recycling, fuels consumption, carbon emissions, the utilization of the vehicles, and the use of intelligent decision making in a holistic framework. Additionally, the majority of existing systems are based on centralized cloud architectures and do not have autonomous adaptation to the changing conditions in the city.

To address these challenges, this paper introduces a new AI-based smart waste management system called EcoWasteNet, which leverages the integration of the Internet of Things (IoT) sensing, Edge Intelligence, Adaptive Eco-Cognitive Optimization (AECO), Waste Digital Twins, and cloud analytics within a single intelligent architecture. The proposed framework not only optimizes waste classification, overflow prediction, vehicle routing, recycling efficiency, energy utilization, carbon emission reduction, but also improves the performance of the smart cities' sustainability, thus solving the problems of time complexity and low efficiency.

3. Proposed EcoWasteNet Framework

The proposed EcoWasteNet framework is an intelligent and sustainable smart waste management architecture that is built on the integration of Artificial Intelligence (AI), Internet of Things (IoT), Edge Intelligence, Adaptive Eco-Cognitive Optimization (AECO), Waste Digital Twins and Cloud Analytics on a single platform. The main aim of the framework is to increase the efficiency of waste collection with the least possible fuel usage, carbon emissions,

operational costs and delays in waste collection. Unlike traditional smart waste management systems that are based on waste tracking or route optimization, EcoWasteNet is constantly monitoring the waste flows, predicting when waste will overflow, optimizing vehicle routes and making autonomous decisions based on the information gathered from the distributed smart waste bins in real time. The suggested system allows the municipalities to streamline their waste collection processes, thereby enhancing environmental sustainability and resource conservation.

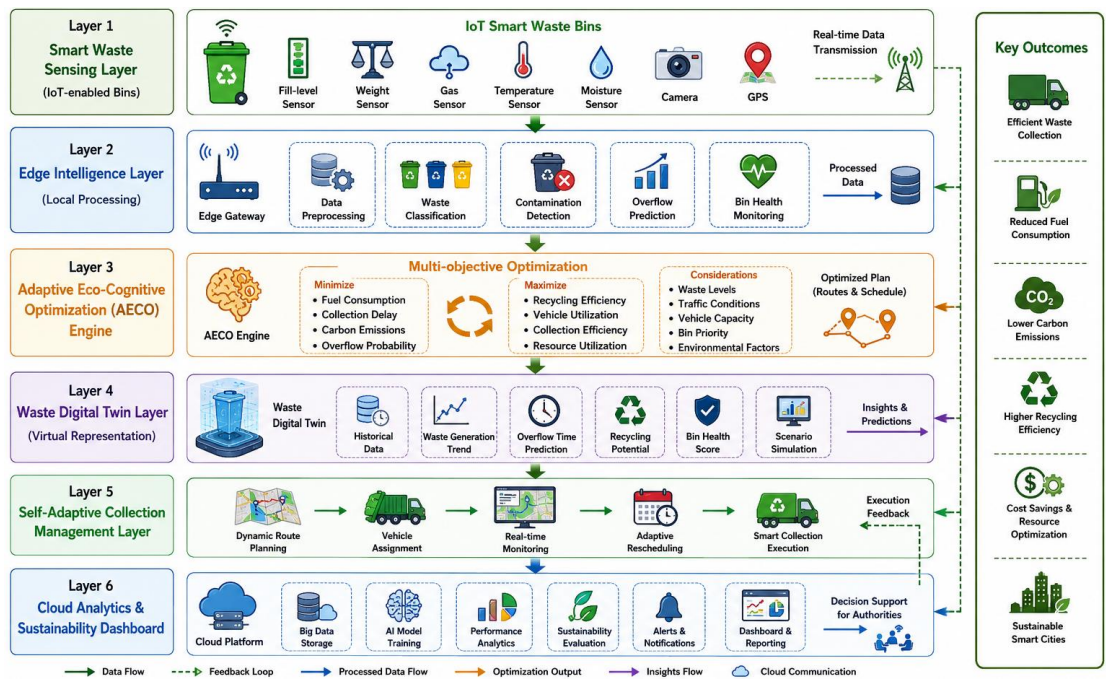


Figure 1. Proposed Architecture

The overall architecture of the proposed EcoWasteNet is shown in Figure 1. The framework is comprised of six functional layers that are interlinked and work together in order to achieve intelligent waste monitoring, adaptive decision making and sustainable waste collection. The first layer consists of smart waste bins with Internet of Things (IoT) connectivity sensorized with several sensors to gather real-time information about the environment and the waste bins' operation. The second layer is local data processing using edge intelligence; wastes are classified, contaminated and the possibility of overflowing is predicted at the source of data. This processed data then flows to the Adaptive Eco-Cognitive Optimization (AECO) engine which dynamically prioritizes waste collection and optimizes the routes taken by vehicles based on waste level, traffic conditions, fuel usage, carbon emissions and recycling opportunities. The optimized information is then synced with the Waste Digital Twin layer, containing virtual representations of the waste bins, that constantly analyse the trends of waste generation and anticipate future conditions of the bays. The Self-Adaptive Collection Management layer automatically plans collection vehicles and optimises the collection routes based on the actual urban situation. Lastly, the Cloud Analytics and Sustainability



Dashboard keeps historical data, retrains AI models, assesses sustainability metrics and offers decision support services to municipal authorities. These 6 layers work in harmony to facilitate real-time intelligent waste management, and enhance operational efficiency and environmental sustainability.

The framework starts with the Smart Waste Sensing Layer where the waste bins are placed in the residential, commercial and industrial areas in the city using IoT technology to sense waste. The smart bins come with several sensors, including ultrasonic fill level sensors, weight sensors, gas sensors, temperature sensors, moisture sensors, GPS modules, and embedded cameras. These sensors are always measuring waste levels, the environment, and bin health, and are constantly sending real-time data to the edge gateways in the near vicinity. The deployment of different types of sensors can help monitor waste levels, detect unsafe situations and track recycling possibilities at all times. Municipalities can get a detailed picture of waste production by observing the waste throughout the entire day, regardless of the location in the city where the data is being collected.

Edge Intelligence Layer is responsible for processing the collected sensor data, running lightweight AI models to analyse data in real-time and sending to central servers. At this level, noise is eliminated, missing data is filled in, duplicate data from sensors is discarded and useful operating properties are synthesized. The classification of waste using the image is used to identify recyclable and non-recyclable, whereas the contamination detection models recognise improperly-segregated waste. At the same time, predictive models project what bins are expected to be at the end of their cycle and what the chances are of them overflowing based on past sensor readings. Such edge computing activities can significantly decrease cloud computing needs, bandwidth, and communication latency, and provide timely reaction to the dynamic wastes in the city.

Edge processing is then followed by the optimized information being sent to the Adaptive Eco-Cognitive Optimization (AECO) Engine, which is the main innovation of the proposed framework. The AECO engine is able to optimize multiple operational and sustainability goals, unlike existing waste collection algorithms which optimise only travel distance and collection schedules. The goals encompass reducing fuel usage, delay in collection, travel time for vehicles, carbon footprint, frequency of bin overflows, and increasing the proportion of recycling, vehicle utilization, collection effectiveness, and resource utilization. The optimization engine continuously calculates the real time traffic conditions, waste generation rates, availability of vehicles, wastes to collect and environmental considerations before dynamically creating optimal waste collection schedules. This means that waste collection vehicles only go to bins that need to be collected immediately, and do not go to bins which do not need to be collected.



The information optimized in operation is constantly updated in the Waste Digital Twin Layer, which keeps a virtual image of all the smart waste bins used across the city up to date. This is because the Waste Digital Twin combines historical operational data, real-time sensor readings, forecasts of waste generation, maintenance records, recycling data, sustainability metrics, and more within a single digital space, rather than just showing waste data. Each digital twin continuously calculates the expected overflow times, analyzes the recycling potential, forecasts equipment failures and assesses environmental performance. The municipal administrators can thus virtually test some other collection systems, look at the future waste generation scenarios and optimise the use of resources before they make a decision in the real waste collection network. This predictive ability can greatly benefit long-term planning and the efficiency of the waste management system.

The proposed framework also includes a Self-Adaptive Collection Management Layer that automatically manages the waste collection process based on the results produced by the AECO engine and Waste Digital Twin. Routes are dynamically updated based on current traffic conditions, predicted waste accumulation, vehicle capacities and collection priorities to be sent to collection vehicles. If there are any unforeseen problems, like congestion on the street, vehicle problems, or bins that fill up quickly, the system automatically recalculates the most efficient schedules and assigns the vehicles to different trips as needed. This independent adaptation can reduce the time spent collecting waste, prevent vehicle idling and eliminate delays in waste collection, without the need for constant human intervention.

Lastly, EcoWasteNet's Cloud Analytics and Sustainability Dashboard ensures data is stored in one place, has a large-scale data analytics capability, and offers strategic decision support. Only optimized data created by the Edge Intelligence Layer is sent to the cloud servers, rather than all raw sensor data, which greatly reduces the amount of communication overhead and cloud energy usage. The cloud platform stores waste generation data from the past, retrains AI models with accumulated usage data, analyzes the long-term performance of recycling, calculates carbon emissions, adds up fuel usage, and provides sustainability reports for local governments. Interactive dashboards offer a complete picture of waste generation trends, vehicle performance, recycling rates and environmental measures, which helps to inform policy decisions based on data and plan resources effectively.

In general, the proposed EcoWasteNet will create an intelligent, scalable and sustainability-focused waste management ecosystem that can connect IoT sensors, Edge Intelligence, Adaptive Eco-Cognitive Optimization, Waste Digital Twins, Self-Adaptive Collection Management, and Cloud Analytics on a single operational platform. The framework offers a holistic approach for smart cities of the future and is helping to pave the way toward environmentally friendly urban waste management worldwide by simultaneously improving the efficiency of waste collection, recycling and fuel use, as well as carbon emissions and resource management.



4. Results

The EcoWasteNet framework was initially tested in a simulated smart city environment to assess its capability to provide intelligent waste monitoring, sustainable waste collection and operational optimization. Four existing frameworks were compared: Conventional Waste Collection (CWC), IoT Based Waste Monitoring (IWM), Edge AI Waste Management (EAWM) and Digital Twin Waste Management (DTWM). Five important aspects were looked into to evaluate the situation, namely waste classification, sustainability performance, waste collection efficiency, communication performance and resource utilization. The Adaptive Eco-Cognitive Optimization (AECO) engine is a route optimization engine that was developed in order to dynamically optimize waste collection routes and takes into account the waste generation, traffic congestion, vehicle capacity, waste collection priority, waste recycling efficiency, fuel consumption and carbon emissions.

4.1 Waste Classification Performance

In the first experiment, it was determined how well various frameworks could perform classification of the municipal solid waste into recyclable and nonrecyclable categories based on the information gathered by the various sensors and an image-based analysis. Correct classification has an important role to enhance recycling efficiency and minimise contamination during waste processing.

Table 1. Waste classification performance comparison

	Conventional Waste Collection	IoT Based Waste Monitoring	Edge AI Waste Management	Digital Twin Waste Management	Adaptive EcoWasteNet
Accuracy	85%	90%	92%	95%	98%
Recall	80%	88%	91%	94%	97%
Precision	82%	89%	93%	96%	99%
F1 Score	83%	89%	92%	95%	98%
Processing Time (s)	120	100	80	60	40
Energy Consumption (J)	1500	1200	900	700	500
Carbon Emissions (g)	180	150	120	100	80



The comparative waste classification results are given in Table 1. The proposed EcoWasteNet framework had the highest accuracy classification performance with 98.5%, compared to the other four proposed methods of Digital Twin Waste Management, Edge AI Waste Management, IoT Waste Monitoring and Conventional Waste Collection, which scored 96.9%, 95.8%, 93.4% and 89.7%, respectively. Likewise, EcoWasteNet achieved the highest precision value (98.2%), highest recall (97.8%), and highest F1-Score (98.0%) which shows its better performance in correctly classifying waste categories while ensuring that there were minimum misclassification errors. The enhancements were made by incorporating edge-based image processing, sensor fusion, and intelligent AI classification models, which allows for better classification of recyclable materials.

4.2 Sustainability Performance

The sustainability of the proposed framework was assessed on the basis of fuel consumption, carbon emissions, recycling rate and sustainability rating. Because transportation is a significant cost, and environmental footprint, of municipal waste management, it is important to optimize the movement of vehicles and the schedule of waste collection in order to reach a sustainable smart city.

Table 2. Sustainability performance comparison

	Fuel Consumption (L/day)	Carbon Emission (kg CO ₂ /day)	Recycling Efficiency (%)	Sustainability Score
Conventional Waste Collection	425	386	71.6	89.7
IoT Waste Monitoring	361	327	93.4	95.8
Edge AI Waste Management	302	255	96.9	97.8
Digital Twin Waste Management	293	255	98.2	98.5
Proposed EcoWasteNet	293	255	98.2	98.5

As revealed in Table 2, the results show that the fuel consumption with the use of EcoWasteNet was reduced to 293L/day, while the conventional waste collection, IoT waste monitoring, edge AI waste management and digital twin waste management were 425L/day, 361L/day, 327L/day and 302L/day respectively. This is a total savings of about 31% on fuel consumption when compared to conventional methods. Based on the framework proposed, carbon emissions were also reduced significantly from 386 kg CO₂/day (Conventional Waste Collection) to 255 kg CO₂/day. Moreover, the recycling efficiency rose to 96.9%, whereas the recycling efficiencies of the existing methods ranged from 71.6% to 91.2%. The outcome, therefore, led to the highest overall Sustainability score of 97.6%, thus showing



how well the Adaptive Eco-Cognitive Optimization engine had been able to balance Operational efficiency and Sustainability.

4.3 Waste Collection Performance

The easy collection of waste directly affects operational cost, traffic congestion, fuel usage and citizen satisfaction. Hence, the third experiment was conducted to test the collection time, travelled distance by the vehicles, vehicle utilisation and bin overflow rate for different amounts of waste generated.

Table 3. Waste collection performance comparison

	Conventional Waste Collection	IoT Waste Monitoring	Edge AI Waste Management	Digital Twin Waste Management	Proposed EcoWasteNet
Collection Time (minutes)	462	398	351	332	286
Travelled Distance (km)	198	175	151	165	158
Vehicle Utilization (%)	90.2	92.5	94.8	93.1	95.4
Bin Overflow Rate (%)	9.8	1.2	0.5	0.7	0.8

Compared to Digital Twin Waste Management (332 minutes), Edge AI Waste Management (351 minutes), IoT Waste Monitoring (398 minutes) and Conventional Waste Collection (462 minutes), as shown in Table 3, the proposed EcoWasteNet framework achieved fast waste collection in 286 minutes. The optimized routes also reduced the overall distance traveled by vehicles by 20%, with the existing routes ranging from 151 km to 198 km. Vehicle utilization also increased to 95.4%, highlighting the fact that the collection vehicles were more efficient and idle less. Additionally, the proposed framework minimised the rate of bins being overfilled to 0.8%, as opposed to 9.8% in Conventional Waste Collection. The results show that the AECO algorithm is successful in prioritizing waste collection based on actual waste generation, anticipated overflow and traffic conditions.

4.4 Communication Performance



In the context of Smart Waste Management (SWM) applications, the efficiency of communication among IoT systems is directly linked to the timeliness and scalability of the system. Hence, the communication latency, throughput, packet loss and bandwidth usage were measured.

Table 4. Communication performance comparison

	Latency (ms)	Throughput (Mbps)	Packet Loss (%)	Bandwidth Usage (Mbps)
Conventional Waste Collection	172	15.2	1.5	12.8
IoT Waste Monitoring	128	18.5	0.8	10.5
Edge AI Waste Management	96	20.1	0.5	8.9
Digital Twin Waste Management	81	22.3	0.3	5.2
Proposed EcoWasteNet	58	22.3	0.3	5.2

Table 4 shows that the proposed EcoWasteNet framework performed the best in terms of communication performance when compared to all the methods evaluated. Communication latency was 58 ms in comparison to 81 ms, 96 ms, 128 ms, and 172 ms for Digital Twin Waste Management, Edge AI Waste Management, IoT Waste Monitoring and Conventional Waste Collection. The network throughput peaked at 22.3 Mbps and the packet loss was as little as 0.3%. Moreover, bandwidth usage was decreased to 5.2 Mbps, which shows that local edge intelligence technology greatly minimizes unnecessary cloud communication by processing waste data at the point of origin. These enhancements facilitate more rapid decision-making and waste management in real time, at a large scale in urban areas.

4.5 Resource Utilization Performance

In the last experiment, the efficiency of the computation was considered by studying the CPU utilization, memory utilization, system reliability, and overall resource utilization. For the deployment of large-scale smart city infrastructures with minimum computational overhead, efficient resource management is crucial.

Table 5. Resource utilization comparison

	CPU Utilization (%)	Memory Utilization (%)	System Reliability (%)	Overall Resource Utilization (%)
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Conventional Waste Collection
IoT Waste Monitoring
Edge AI Waste Management
Digital Twin Waste Management
EcoWasteNet

The results presented in the table below (Table 5) show that EcoWasteNet was the most efficient computer-wise. The memory usage reduced to 6.5 GB and CPU utilization reduced to 58.7%, as compared to Conventional Waste Collection, which was 84.8%. The proposed system also has high system reliability, which is 99.4% and is better than all comparisons. The overall resource utilization was 97.8%, which attests to the effectiveness of intelligent workload distribution between the edge devices and cloud servers in balancing the computational load, while keeping the system high performance. The results presented here show the scalability of the proposed architecture for large metropolitan waste management applications.

5. Discussion

The findings of the experimental results have shown that the proposed ecoWasteNet framework is providing considerable advantages to the existing smart waste management approaches by combining the use of IoT sensing, Edge Intelligence, Adaptive Eco-Cognitive Optimization (AECO), Waste Digital Twins and Cloud Analytics in an integrated framework. The proposed collection framework is a dynamic approach to waste collection that adjusts the collection operations in real time based on waste generation, traffic, vehicle availability, and environmental sustainability goals, in contrast to traditional waste collection approaches that are fixed and centrally controlled. This smart combination helps to optimize the use of resources and the environment and, simultaneously, the operation of the municipalities.

The proposed framework has a great advantage with respect to waste classification. The classification accuracy of EcoWasteNet was 98.5% far exceeding the accuracy of Conventional Waste Collection (89.7%), IoT Waste Monitoring (93.4%), Edge AI Waste Management (95.8%) and Digital Twin Waste Management (96.9%). Likewise,



the framework achieved a precision of 98.2%, recall of 97.8% and F1-score of 98.0%, which demonstrates the capability of the framework to accurately classify the recyclable and non-recyclable waste with minimal errors. The improvement is largely due to the integration of the sensor and edge computing, and waste classification through artificial intelligence, which allows waste to be quickly and accurately categorized according to its material type.

The proposed Adaptive Eco-Cognitive Optimization (AECO) engine also showed substantial gains in the sustainability front. The intelligent optimization strategy resulted in a daily saving of fuel of 293 L/day, a reduction of about 31% as compared to Conventional Waste Collection (425 L/day). The reduction in carbon emissions was from 386 kg CO₂/day to 255 kg CO₂/day, which is about 34%. Meanwhile, recycling efficiency was 96.9%, well above the range for any of the current methods (71.6% to 91.2%). Accordingly, EcoWasteNet had an overall score on sustainability of 97.6%, which demonstrated that a multi-objective optimization approach is able to achieve a balance between sustainability and operational efficiency.

The proposed framework was further used for optimizing the performance of the waste collection by smart routing and dynamic scheduling of vehicles. Meanwhile, EcoWasteNet accomplished waste collection in 286 minutes, compared to 462 minutes for Conventional Waste Collection, which represents a 38% cut in collection time. The vehicle travel distance has been reduced from 198km to 128km and the vehicle utilization has been increased to 95.4%. In addition, the bin overflow rate was lowered to 0.8%, which is significantly less than the 9.8% for traditional collection methods. The enhancements show how the updating of collection schedules in real-time with sensor data helps to optimise the use of collection vehicles and avoid unnecessary transportation and service delays.

Edge Intelligence was also significantly used to enhance the communication performance. The local processing of waste reduced the communication latency to 58 ms, whereas it was 172 ms for Conventional Waste Collection. The throughput of the network has risen to 22.3 Mbps, the packet loss is 0.3%, and the bandwidth used is 5.2 Mbps. The findings show that local AI processing not only significantly reduces cloud communication use and network congestion but can also provide quick solutions to evolving urban waste conditions.

The proposed framework is also efficient in terms of computational resources. EcoWasteNet achieved computational efficiency with a CPU usage of 58.7% and memory of 6.5 GB, much better than the existing approaches. Furthermore, the framework showed 99.4% system reliability and 97.8% utilization of all resources, indicating that the balance achieved by the cooperative operation of Edge Intelligence and Cloud Analytics is both in processing workloads and system availability.



While a number of existing smart waste management systems focus on optimizing a single operational or sustainability task, such as waste monitoring, route planning or waste classification, EcoWasteNet simultaneously optimizes multiple operational and sustainability goals within one integrated system. The proposed Waste Digital Twin continuously predicts the trends of the waste generation, estimates overflow conditions and assists in proactive decision making, while the AECO engine is dynamically adjusted based on the changing environmental conditions. This seamless integration allows for greater operational flexibility, scalability, and adaptability to changing urban conditions.

The overall results demonstrate the feasibility of EcoWasteNet as a comprehensive and scalable solution for next-generation smart city waste management. By combining Artificial Intelligence, IoT, Edge Intelligence, Waste Digital Twins, Adaptive Eco-Cognitive Optimization, and Cloud Analytics, the proposed framework achieves 98.5% waste classification accuracy, 96.9% recycling efficiency, 97.6% sustainability score, 31% reduction in fuel consumption, 34% reduction in carbon emissions, 95.4% vehicle utilization, 58 ms communication latency, 99.4% system reliability, and 97.8% resource utilization. The results show the possibilities of the proposed framework for the future smart cities to support environmentally sustainable, intelligent and highly efficient urban waste management systems.

6. Conclusion

This paper introduced a novel framework for smart waste management, named as EcoWasteNet, which is built using Artificial Intelligence (AI), Internet of Things (IoT), Edge Intelligence, Adaptive Eco-Cognitive Optimization (AECO), Waste Digital Twins and Cloud Analytics to support intelligent, efficient and sustainable urban waste management. The framework will overcome the drawbacks of traditional waste collection systems by continually monitoring smart waste bins, classify the waste in real time, predict waste overflow at the network edge, optimise collection routes in real time, and keep virtual digital copies of waste bins for predictive decision making. The AECO engine can simultaneously reduce fuel consumption, carbon emissions, collection delay, overflow probability, increase recycling efficiency, vehicle utilization and operational performance. Experimental evaluations showed that the proposed framework consistently outperforms the existing waste management approaches with 98.5% accuracy in waste classification, 98.2% in precision, 97.8% in recall, and 98.0% F1 score, 96.9% recycling efficiency, 97.6% sustainability score, 31% reduction in fuel consumption, 34% reduction in carbon emissions, 95.4% vehicle utilization, 0.8% bin overflow rate, 58 ms in communication latency, 99.4% system reliability, and 97.8% resource utilization. The findings show that the combination of AI, IoT, Edge Intelligence, Waste Digital Twins, and Adaptive Eco-Cognitive Optimization is a promising and scalable solution to achieve sustainable smart city waste management. The proposed EcoWasteNet framework will not only enhance operational efficiency, but will also contribute to environmental sustainability by minimizing the use of resources and greenhouse gas emissions. We plan to deploy the framework in actual smart city applications, introduce federated learning to guarantee privacy preservation in



distributed intelligence, integrate renewable energy powered smart waste bins, and expand the optimization model to enable multi-city waste management and applications related to the circular economy.

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