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Review Article

Fusion of Blockchain, IoT, Artificial Intelligence, and Robotics for Efficient Waste Management in Smart Cities

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Abstract

Rapid urbanization and population growth are accelerating waste generation in cities worldwide, posing serious environmental and socio-economic challenges. Traditional waste management systems, often centralized and infrastructure-deficient, struggle with inefficiencies, unscheduled collection, and a lack of real-time data. These limitations hinder progress toward smart and sustainable urban environments. Blockchain, the Internet of Things (IoT), Artificial Intelligence (AI), and Robotics are reshaping waste collection, sorting, and recycling. This review examines how these technologies integrate to create secure, efficient, and sustainable waste management in smart cities. An analysis of 184 studies published between January 2022 and July 2025 reveals key shortcomings in conventional waste management systems and showcases the benefits of smart waste management solutions. The results showed that cities are already using IoT-enabled smart bins, AI-driven route optimization, Blockchain for waste tracking, and robotic sorting. However, challenges such as data privacy concerns, limited Blockchain scalability, system interoperability gaps, sensor reliability issues, and high computational demands limit broader adoption. The review outlines future research priorities, including AI-powered waste forecasting, swarm robotics, real-time edge computing, and enhanced cybersecurity. By providing a roadmap for technological innovation and integration, this study supports policymakers, urban planners, and industry leaders in developing intelligent, cost-effective, and environmentally resilient waste management systems.

Keywords: Waste Management; Smart Waste Management; Blockchain Technology; Internet of Things; Artificial Intelligence; Robotics.

INTRODUCTION

Urban population growth and expanding industrial activities have dramatically increased daily waste production, escalating the global challenge of managing waste effectively. As a result, existing waste management systems struggle to cope with the growing volumes of domestic and industrial liquid, gaseous, and solid waste [1]. Mor and Ravindra [2] define waste as materials, substances, or byproducts that people discard when they are no longer helpful, needed, or wanted. It includes solid, liquid, or gaseous materials produced through human activities, such as household trash, industrial byproducts, agricultural residues, and electronic discards. In recent years, the rapid increase in the volume and complexity of waste, including municipal solid waste, industrial byproducts, hazardous materials, and electronic waste, has intensified environmental pollution, depleted natural resources, and heightened public health risks [2]. Research identifies industrial waste as the primary contributor, comprising volatile compounds, wastewater, slag, and scrap that often contain hazardous substances such as heavy metals, organic pollutants, and radioactive materials. These materials can cause severe environmental damage if not disposed of properly. Organic waste, generated from agricultural and animal activities, wastewater treatment, and the food industry, also poses risks despite its potential for composting or reuse. Toxic compounds, such as ammonia and chlorine, even in natural organic waste, can pollute air, water, and soil. Solid waste, produced through manufacturing, agriculture, and mining, is typically managed through recycling, incineration, or landfilling. Hazardous waste often originates from biomedical and electronic sources and contains toxic, flammable, or radioactive elements. Liquid waste, such as mercury and cyanide-containing fluids, poses a significant threat, with heavy metal liquids accounting for nearly half (47.9%) of the total. Recyclable waste includes materials that can be extracted from the waste stream and reused as raw materials, such as paper, glass bottles, and ceramics, through biological, energy, or physical re-treatment techniques [3]. Plastics, a major non-biodegradable pollutant, make up 18.4% of global waste, ranking second only to food waste and posing severe long-term environmental challenges [4].

Cities around the world currently generate over 2 billion tons of municipal solid waste annually, a figure projected to increase to 3.4 billion tons by 2050 [5]. Individuals generate between 0.11 and 4.54 kilograms of waste per day. Municipalities spend approximately US$375.5 billion annually on waste management [6]. Recent findings indicate that 33% of urban solid waste is not disposed of in a safe or environmentally friendly manner [7]. This mismanagement, combined with shrinking landfill space and the adverse environmental effects of improper disposal, has elevated municipal solid waste to a critical global challenge [8]. The growing volume of waste demands urgent and innovative solutions to ensure environmental sustainability and protect public health.

Waste management is defined as the process of managing waste from disposal to demolition [9]. Effectively managing the increasing volume of waste presents a significant challenge, as communities and authorities struggle to keep pace with rising consumption and inadequate disposal systems. Traditional waste management systems, which rely on fixed collection schedules, manual sorting, and landfill disposal, increasingly fail to keep pace with rising waste volumes. These outdated approaches often lead to overflowing bins, inefficient collection routes, excessive fuel consumption, greenhouse gas emissions, high operational costs, environmental degradation, public health risks, and marine pollution [1, 8, 10, 11]. The lack of real-time data, transparency, and standardized practices further weakens the effectiveness of these systems, hindering timely issue resolution and reducing public trust. Moreover, insufficient infrastructure, poor segregation, inadequate recycling facilities, and limited public awareness exacerbate inefficiencies [12]. Conventional methods remain time-consuming, labour-intensive, and prone to errors, contributing to mismanagement, unsanitary conditions, and the spread of disease. Globally, such inefficiencies account for 3–5% of anthropogenic greenhouse gas emissions, significantly harming ecosystems [13].

As waste generation continues to outstrip system capacity, the urgent need for innovation in waste management has become increasingly apparent. Researchers and engineers are increasingly leveraging emerging technologies, such as Blockchain, IoT, AI, and robotics, to develop smart waste management solutions that support the goals of smart cities [14]. Smart waste management is the use of advanced technologies, such as sensors, data analytics, the IoT, and AI, to optimize waste collection, sorting, recycling, and disposal. By enabling real-time monitoring, efficient resource allocation, and data-driven decision-making, these systems reduce environmental impact, cut operational costs, and enhance sustainability in waste handling [1]. Modern waste management increasingly relies on integrated technologies, such as IoT-enabled monitoring, smart bins, AI, robotics, and Blockchain, to enhance every stage of the process, from collection and transportation to treatment, recycling, and disposal. These technologies work together to create efficient, sustainable, and environmentally responsible systems that minimize waste generation, maximize resource recovery, and support the circular economy, thereby reducing the ecological footprint [8, 15]. IoT devices, including sensors and smart bins, gather real-time data on waste levels, locations, and types, enabling route optimization, cost reduction, and lower greenhouse gas emissions [16]. AI analyses this data to forecast waste patterns, dynamically adjust collection schedules, and automate high-precision sorting using deep learning and convolutional neural networks (CNNs), a class of deep learning models specifically designed to process data arranged in grid-like structures, such as images or time series, by applying learnable filters to capture local patterns and spatial hierarchies. Meanwhile, You Only Look Once (YOLO) v11 enhances real-time object detection for waste segmentation [17, 18]. Robotics powered by AI streamlines hazardous material handling, sorting, and recycling tasks, reducing human risk and improving efficiency. Blockchain ensures transparency and trust by recording tamper-proof transactions, enabling secure machine-to-machine communication, real-time tracking, smart contracts, and token-based incentives [16, 19]. Together, these technologies allow diverse smart city applications, such as decentralized recycling platforms, robotic street cleaning, organic waste-to-energy systems, illegal dumping detection, and citizen reward apps, while supporting the United Nations Sustainable Development Goals (SDGs), particularly SDG

11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 14 (Life Below Water) and advancing broader urban sustainability objectives [8, 20-28]. These technologies enable end-to-end digitalization by powering citizen engagement apps that reward responsible behaviour and by optimizing fleet management and environmental compliance [7, 19]. Together, they enhance efficiency through real-time responsiveness and automation, strengthen security and trust by utilizing Blockchain's decentralized, tamper-proof ledger, and advance sustainability through data-driven approaches to recycling and emission reduction [29-38].

This study offers a comprehensive analysis of how Blockchain, IoT, AI, and Robotics can collaborate to revolutionize waste management in smart cities. It examines the current applications of these technologies, their limitations, and the future directions required to develop sustainable urban ecosystems. By examining their integration, the study reveals how these technologies can address the shortcomings of traditional waste management systems. Drawing on recent advancements, it offers practical insights to guide policymakers, practitioners, and researchers in building resilient, efficient, and transparent waste management infrastructures.

Several recent studies have explored the use of emerging technologies in smart waste management, but few have examined their combined potential. Alabdali [26] proposed an AI-based waste classification system that incorporates IoT and Blockchain, while Palagan et al. [25] introduced a federated learning and Blockchain framework for real-time waste prediction. Santhuja et al. [39] developed an e-waste solution using IoT, Blockchain, and CNNs to support circular economy initiatives. Gulyamov [40] investigated the use of IoT, Blockchain, big data, and AI in building smarter waste systems. Other studies, such as those by Ashwini et al. [41] and Addas et al. [42], focused on biomedical and general waste management using IoT, computer vision, and cloud analytics. However, none of these studies fully address the integrated application of Blockchain, IoT, AI, and Robotics. This research fills that gap by analysing how their convergence can overcome existing challenges, enhance sustainability, improve operational efficiency, and support the development of cleaner and more liveable urban environments.

The significant contributions of this study are as follows:

- To present the background and fundamental concepts of smart waste management.
- To explore the roles of Blockchain, IoT, AI, and Robotics in efficient waste management for smart cities.
- To explain the application of technological fusion for efficient waste management in smart cities.
- To describe the real-world scenarios of the fusion of Blockchain, IoT, AI, and Robotics in efficient waste management for smart cities, and how these technologies are being implemented across different regions.
- To identify the challenges and limitations encountered while implementing the technological fusion in efficient waste management for smart cities.
- To highlight the future research directions and opportunities in this field.

This review paper is structured as follows: Section 2 describes the materials and methods used in the study. Section 3 presents the background and foundational concepts. Section 4 explores the roles of Blockchain, IoT, AI, and Robotics in efficient waste management for smart cities. In contrast, Section 5 describes the fusion of these emerging technologies and their applications in efficient waste management for smart cities. Section 6 examines the real-world scenarios of the fusion of Blockchain, IoT, AI, and Robotics in efficient waste management for smart cities. Section 7 outlines the challenges and limitations encountered during the implementation of these technologies in efficient waste management for smart cities. Section 8 highlights the future research directions and opportunities in this field, and Section 9 concludes the study.

MATERIALS AND METHODS

This review systematically collects, evaluates, analyzes, and organizes literature on the fusion of Blockchain, IoT, AI, and Robotics for efficient waste management in smart cities. It emphasizes interdisciplinary integration by identifying thematic trends, technological synergies, and implementation challenges. To ensure broad and relevant coverage, the study conducted a comprehensive literature search across multiple scientific databases and digital libraries, including PLoS ONE, Frontiers, ACM Digital Library, IGI Global, Nature, Springer, ScienceDirect, MDPI, IEEE Xplore Digital Library, and Google Scholar, with a focus on peer-reviewed journal articles, conference proceedings, and book chapters. The search covered publications from January 2022 to July 2025 to capture the evolution of digital technologies in urban waste management. To ensure relevance, the researchers employed specific keywords and Boolean combinations tailored to each database, thereby optimizing the search results for each database. These included terms such as "Smart City" AND "Waste Management," "Blockchain" OR "Distributed Ledger," "Municipal Solid Waste" OR "E-waste," "IoT" OR "Internet of Things" AND "Waste Monitoring" OR "Smart Bins," "Artificial Intelligence" OR "Machine Learning" AND "Waste Classification" OR "Optimization," and "Robotics" AND "Waste Collection" OR "Autonomous Waste Sorting" OR "Fusion" OR "Integration" AND "Blockchain" AND "IoT" AND "AI" AND "Robotics" to target studies addressing integrated technological approaches. The researchers used Boolean operators to refine search results across the subdomains related to the fusion of Blockchain, IoT, AI, and Robotics for efficient waste management in smart cities, ensuring the inclusion of only relevant studies. The researchers refined the search strings to align with the functionalities of each database, ensuring the inclusion of only the most pertinent literature related to the fusion of these technologies for efficient waste management in smart cities.

To ensure the relevance and quality of this review, the researchers applied specific inclusion and exclusion criteria that guided the selection of studies. This review includes research studies that focus on at least one of the following technologies like Blockchain, IoT, AI, or Robotics specifically in the context of waste management. It considers publications that explicitly address waste management systems within urban or smart city environments, including aspects such as smart infrastructure, urban governance, and digital urban planning. To ensure scholarly rigor, the review includes only peer-reviewed journal articles, reputable conference proceedings, book chapters from recognized institutions, and official technical reports from reputable institutions. It prioritizes studies that present a conceptual model, prototype, algorithm, or real-world implementation related to waste monitoring, segregation, routing, recycling, or automation. Only high-quality research with transparent methodology and significant theoretical or empirical contributions has been considered for inclusion. The review includes only studies written in English and published between January 2022 and July 2025 to maintain consistency and capture recent technological advancements. The review excluded research studies not published in English to avoid challenges in accurate interpretation and translation. It also excluded grey literature, preprints, white papers, theses, and reports that had not undergone peer review to ensure scientific rigor. Studies that focused solely on Blockchain, IoT, AI, or Robotics without integrating at least two of these technologies within the context of waste management were excluded, as were those unrelated to smart city or urban waste management. The researchers removed duplicate studies or multiple reports from the same project, retaining only the most comprehensive or recent version. They excluded studies that lacked technical depth, implementation details, or evaluation metrics, as well as those with unclear methodologies or insufficient scientific rigor. Finally, the researchers excluded studies published before January 2022 if they did not reflect the current state of technological development in the targeted domains.

Five authors independently searched selected research databases using predefined key criteria, including the title, authors, and publication year; objectives and research questions; study design; methods of analysis; results; conclusions; fusion of Blockchain, IoT, AI, Robotics, or their hybrid; integration of Blockchain, IoT, AI, and Robotics for efficient waste management in smart cities; and challenges and limitations. They then organized the extracted data into a consistent format to ensure uniformity and accuracy. The researchers independently screened the initial database search results to remove duplicates and assess relevance. They first evaluated titles and abstracts, then conducted a detailed full-text review of papers that met preliminary criteria, applying predefined inclusion and exclusion standards to confirm eligibility. To minimize bias, the reviewers used a test-retest method, repeatedly re-evaluating randomly selected papers to ensure consistency and accuracy throughout the selection process.

The researchers identified over 5,236 publications through academic search engines and databases. After removing duplicates and screening abstracts, they narrowed the dataset to 2,687 publications and then assessed each for eligibility, reducing the number to 1,256. Finally, they selected 184 publications that met the study's inclusion criteria. The final analysis systematically examined 184 research studies selected from various digital libraries, focusing on the integration of Blockchain, IoT, AI, and Robotics for efficient waste management in smart cities. The selection included 1 study from PLoS ONE, 1 from Frontiers, 2 from ACM Digital Library, 3 from IGI Global, 3 from Nature, 7 from Springer, 24 from ScienceDirect, 18 from MDPI, 53 from IEEE Xplore Digital Library, and 72 from Google Scholar. Figure 1 summarizes the categorization and relevance of these studies to the research focus.

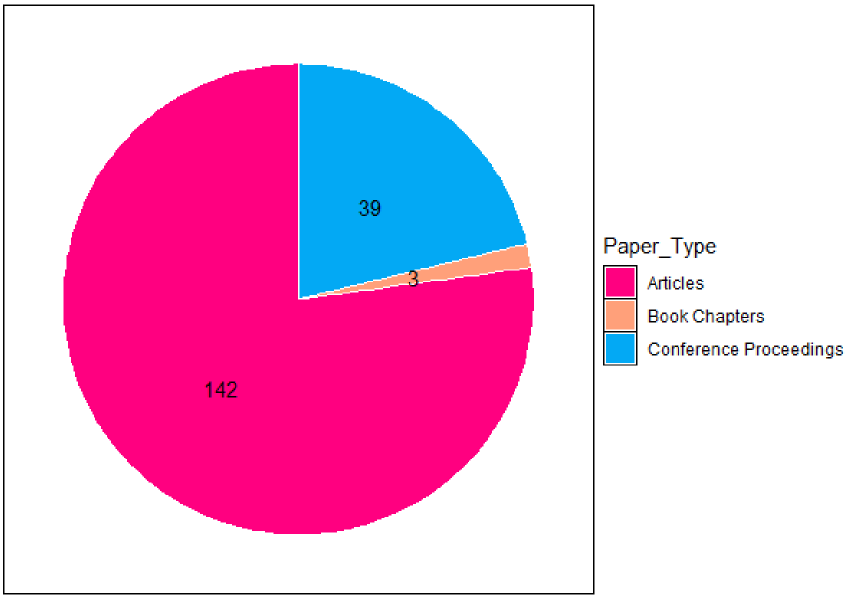

Figure 1. Categorizes the research papers selected for the study.

Figure 2 illustrates the digital databases from which we retrieved the research papers selected for this review.

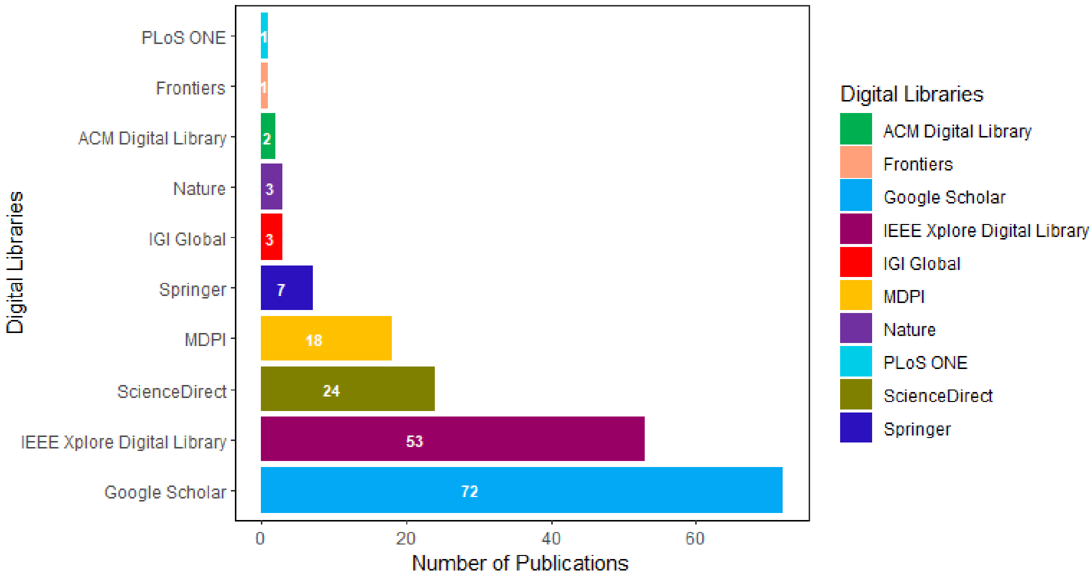

Figure 2. Illustrates the digital databases from which the selected research papers were retrieved.

Figure 3 illustrates the distribution of research papers across various digital libraries.

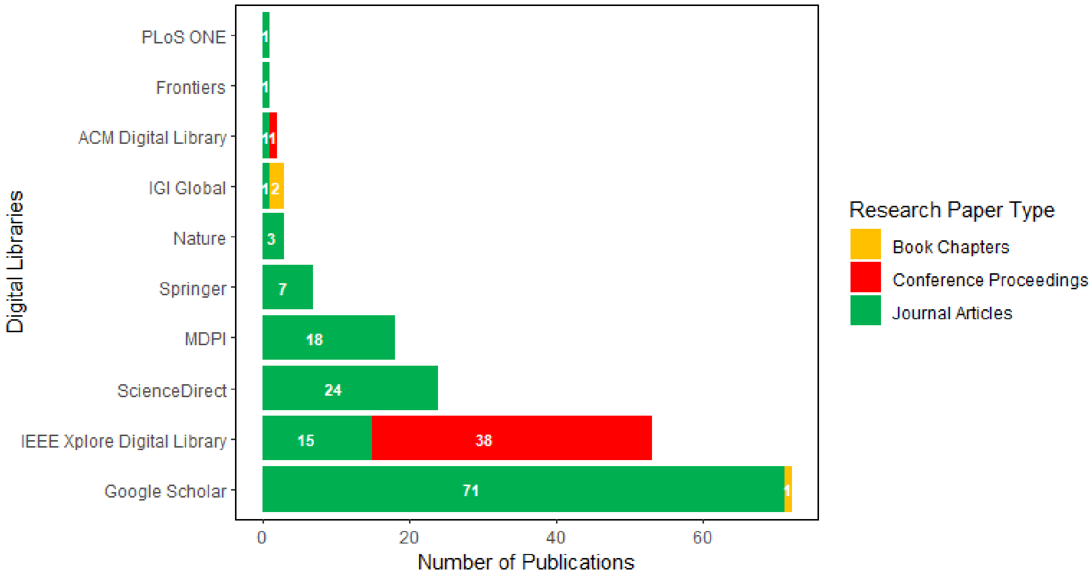

Figure 3. Illustrates the distribution of research papers across various digital libraries.

Figure 4 illustrates the distribution of selected papers from various digital libraries across publication years.

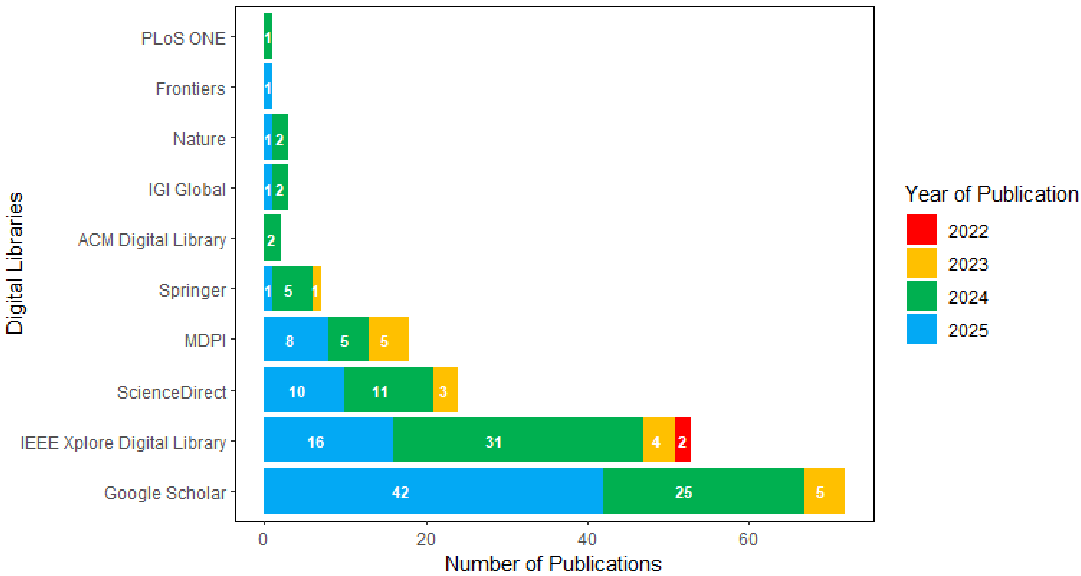

Figure 4. Illustrates the distribution of selected papers from various digital libraries across publication years.

The researchers selected papers by applying criteria such as timeliness, citation count, relevance, methodological rigor, coherence, validity, dependability, peer-review status, source credibility, potential bias, and confounding variables. They conducted comprehensive database searches, meticulously documented all references, created a dedicated reference database, and utilized a reference management tool to eliminate duplicates. Next, they refined the selection through a multi-step screening process involving keyword analysis, title and abstract review, and full-text evaluation. At each stage, they recorded exclusion reasons and discarded studies that did not meet eligibility criteria. Finally, they compiled the remaining papers into a final database for analysis.

The researchers conducted a qualitative synthesis and applied thematic analysis to examine the collected material. They validated their findings by consulting subject-matter experts, comparing the results with those of prior studies, and critically assessing the validity of their conclusions. They selected only high-quality research papers, using a grading system that evaluated methodological rigor, reliability of findings, and relevance to integrating Blockchain, IoT, AI, and Robotics for efficient waste management in smart cities. Since the study relied exclusively on previously published research, it did not require ethical approval; however, the researchers ensured all sources were cited correctly.

Between 2023 and 2025, evaluations and systematic or empirical studies consistently demonstrated that integrating IoT, AI, and robotics into waste management systems significantly improved operational efficiency and sustainability. IoT-based route optimization reduced fuel consumption by approximately 15–35%—with pooled real-world estimates clustering in the low 20% range—and a notable city-scale deployment achieved a 29% reduction, alongside lower emissions, despite high heterogeneity ($I^2 > 70\%$) from baseline routing inefficiencies, fleet age, and geographic density [42, 43]. IoT sensor and analytics solutions also enhanced route efficiency by 20–35%, with larger gains when replacing schedule-driven collection with demand-driven models [42]. Real-time fill monitoring reduced collection frequency by 10–25% and decreased overfilled bins by a similar margin, directly lowering operating costs [43]. AI-powered sorting, smart bin feedback, and incentive programs increased recycling rates by 10–30 percentage points (20–30% relative increase), particularly when AI vision and robotic pickers were combined with behavioral interventions [4, 44]. Furthermore, robotics and AI-based sorting, which utilize computer vision and robotics, have improved accuracy, purity, and recovery rates compared to manual methods. Blockchain primarily adds traceability and quality assurance, rather than enhancing throughput [19, 26].

Recent empirical pilots and field studies that deploy combinations of blockchain, IoT, AI, and robotics in urban waste systems have demonstrated measurable performance gains in operational costs, resource efficiency, and sustainability. IoT-enabled smart bins, paired with AI-driven routing, consistently reduce collection distances and fuel use by approximately 30–40%, resulting in proportional reductions in CO_2 emissions [43, 45]. Dynamic route optimization based on real-time fill data reduces collection frequency and minimizes empty or overflow events, resulting in cost savings of approximately 7–36% depending on the baseline and scale [46]. Blockchain-based tracking and incentive mechanisms, including tokenization and traceability, enhance recycling and collection rates while increasing transparency, resulting in measurable increases in recovered materials and financial benefits for collectors [19]. At sorting facilities, integrating AI with robotics raises throughput and diversion rates by combining accurate classification models with automated sorters, which accelerate cycle times, improve material recovery, and reduce reliance on manual labor [8, 26].

The study faces several limitations: it may have missed relevant studies outside the selected databases and included research that was published in languages other than English but translated into English. The review does not fully address the integration of Blockchain, IoT, AI, and Robotics for efficient waste management in smart cities. By focusing on theoretical applications, the review overlooks practical challenges, including cost, scalability, user acceptance, and real-world implementation barriers. Finally, the rapid advancement of these technologies may have outpaced the literature covered in the review, limiting its current relevance.

BACKGROUND AND FOUNDATIONAL CONCEPTS

Overview of Smart Cities

Bimpas et al. [47] and Denis et al. [48] define smart cities as urban environments that deploy advanced digital technologies, such as the IoT, AI, data analytics, and edge computing, to improve residents' quality of life, streamline city services, reduce pollution, and promote sustainable economic and environmental development. These cities integrate a wide array of technologies, including sensors, smart devices, 5G networks, robotics, digital twins, Web 3.0, smart grids, and big data analytics, to form an interconnected urban ecosystem. By integrating these tools into infrastructure systems such as transportation, energy, building automation, and waste management, smart cities optimize resource utilization and service delivery. They utilize real-time monitoring and data-driven decision-making to alleviate traffic congestion, improve public safety, and mitigate environmental impact. Through this technology-driven approach, smart cities foster liveability, sustainability, and economic growth [47, 48].

The global smart cities market is poised for substantial growth, with revenue projected to reach US$79.94 billion by 2025 and continue to expand at a compound annual growth rate (CAGR) of 9.60% through 2029, ultimately reaching US$115.33 billion by 2029. The United States is expected to lead in revenue generation, contributing an estimated US$27.06 billion in 2025. Globally, countries such as Singapore and South Korea are at the forefront of implementing smart city initiatives, driving innovation and development in this sector.

Smart cities integrate interconnected systems that respond intelligently to real-time data and citizen needs, enabling data-driven decisions and innovative solutions to challenges such as population growth, traffic congestion, pollution, and energy consumption. These cities feature components such as smart buildings, transportation, energy, communications, and networks, all supported by technologies like the IoT and big data analytics [49]. They promote efficient public services, digital healthcare, and participatory governance, exemplified by initiatives like Singapore's Smart Nation, which leverages open data, crowd-sourced navigation, and online civic engagement [49]. Beyond physical infrastructure, smart cities invest in human and social capital—emphasizing education, creativity, and digital inclusion—to foster a smart economy, effective governance, and sustainable urban living. This comprehensive approach strengthens human-technology interaction and supports inclusive and sustainable urban planning [48].

As urbanization and consumption increase, households, businesses, and public spaces in smart cities generate growing volumes of diverse waste, including municipal solid waste, recyclables, organic matter, hazardous materials, and e-waste [50]. To overcome the limitations of traditional waste systems, smart cities deploy AI, IoT, and sensor-equipped smart bins to monitor waste levels, optimize collection routes, and improve sorting accuracy [51]. These technologies enable real-time waste tracking, reduce operational costs, and mitigate environmental impacts by preventing overflow and illegal dumping. Cities also apply data-driven approaches to waste characterization, lifecycle tracking, and resource recovery, advancing the transition to a circular economy [50]. Despite these advances, challenges persist in integrating technologies, safeguarding data privacy, and encouraging community participation in sustainable waste practices. Smart cities view waste not merely as a byproduct, but as a resource for innovation, efficiency, and sustainability, achieved through intelligent systems and collective action [51].

Waste management

Waste management poses a critical global challenge, especially in the cities of developing countries, where limited resources, weak infrastructure, and ineffective policy frameworks hinder effective waste handling and disposal. Rahman et al. [52], Boostani et al. [53], and Anya [28] define waste management as a systematic approach that involves generating, separating, collecting, storing, transporting, processing, recycling, treating, and disposing of waste materials. This process aims to minimize negative impacts on public health, protect the environment, maintain urban aesthetics, and ensure compliance with regulatory standards. For over a century, researchers and companies have explored waste analysis and real-world applications, focusing on strategies such as prevention, minimization, proper collection, transportation, treatment, and regulation of waste processes. Waste can appear in solid, liquid, or gaseous forms, each requiring specific management methods. This field encompasses a diverse range of materials, including both biodegradable and non-biodegradable waste generated from households, industries, agriculture, and other sectors [53].

Management techniques span from traditional approaches like landfilling and incineration to advanced technologies such as anaerobic digestion, pyrolysis, plasma gasification, recycling, and composting. These methods aim to reduce environmental impact, recover resources, and support sustainable development. Waste management responsibilities vary globally, i.e., developed countries typically implement structured systems with advanced technologies, while developing nations often struggle with limited infrastructure and financial constraints. Additionally, urban and rural areas, as well as residential, commercial, and industrial sectors, require customized waste management solutions [28].

By 2025, global waste generation is expected to reach approximately 3.5 billion tonnes, with municipal solid waste, including food and green waste, accounting for a significant share. The municipal solid waste market is projected to grow to US$123.74 billion with a CAGR of 4.6%. In comparison, the broader solid waste management market is anticipated to reach US$330.51 billion, growing at a CAGR of 5.0%. The construction and demolition waste market is also expected to expand, reaching US$217.91 billion with a CAGR of 6.6%. This growth is driven by rapid urbanization, economic development, and increased awareness of sustainable waste practices. Currently, over 2 billion tonnes of municipal solid waste are generated annually, with projections indicating a rise to 3.5 billion tonnes by 2050. Additionally, global plastic waste is projected to reach 460 million tonnes annually by 2025, with 91% of it remaining unrecycled. Each year, an estimated 1.3 billion tonnes of food—about one-third of all food produced—is wasted.

In smart cities, conventional waste management systems typically operate on fixed schedules, where residents deposit waste in bins and municipal trucks collect it for transport to recycling or disposal sites. These systems rely on route-based collections that overlook real-time bin fill levels, frequently resulting in overflowing containers, inefficient fuel usage, and high operational costs [50, 51]. Urban areas commonly employ a combination of landfill disposal, incineration, composting, and recycling, with open-air incineration and secure landfilling remaining prevalent. Most municipalities lack real-time data on bin status, which limits their ability to optimize collection routes or respond quickly to full bins. Manual monitoring persists, and limited source separation further reduces recycling rates, increasing reliance on environmentally damaging landfill practices [50, 51].

Despite their foundational role, traditional waste management systems remain labour-intensive and outdated, struggling to adapt to rapid urbanization, evolving waste streams, and limited public participation [50]. These systems often suffer from inefficiencies, including outdated routes, a lack of real-time monitoring, poor data utilization, and low recovery rates [51]. In many cities, most waste still ends up in landfills or is openly burned, both of which are costly and harmful to the environment [52]. Weak legislation, insufficient funding, poor enforcement, and low public awareness further undermine progress. Informal recycling contributes to pollution and improper waste handling. Urban waste management continues to face significant challenges, including fragmented governance, financial constraints, and inadequate community engagement. While some regions, such as the UK, have adopted more sustainable practices, including kerbside recycling and organic waste collection, challenges persist in boosting participation and reducing emissions from incineration and landfilling [28]. Recent research emphasizes the importance of integrating data-driven technologies and fostering stakeholder collaboration to modernize waste management systems, aligning them with sustainability and public health objectives.

Smart Waste Management

Traditional waste management methods often fail to address the growing complexities of urban waste, underscoring the need for advanced, data-driven solutions. To tackle this challenge, smart waste management leverages technology to shift waste handling from linear, resource-heavy practices to more efficient and circular systems. Boostani et al. [53] define smart waste management as the use of advanced technologies, such as the IoT, data analytics, Blockchain, and AI, to optimize waste handling, reduce environmental impact, and enhance the overall efficiency of waste management systems.

Smart waste management leverages advanced technologies to streamline the entire waste cycle from collection and separation to treatment, disposal, and final disposal. IoT-enabled smart bins with real-time sensors monitor fill levels and environmental conditions, transmitting data to centralized platforms that dynamically optimize collection routes, thereby reducing fuel consumption, operational costs, and emissions [50, 54]. AI enhances efficiency by forecasting waste generation, automating high-precision sorting, and supporting waste-to-energy and resource recovery processes [50]. Cloud-based systems promote transparency and collaboration by facilitating data sharing and informed decision-making among stakeholders [50, 54]. Meanwhile, Blockchain technology ensures secure, transparent, and traceable transactions, thereby enhancing regulatory compliance and auditability. Together, these technologies boost recycling rates, reduce landfill dependence, and support circular economy practices [50]. Researchers emphasize the importance of integrating product lifecycle data, enhancing upstream waste separation, and engaging communities to improve material recovery and minimize waste. They also call for continued innovation, robust policy frameworks, and stakeholder collaboration to address issues like data privacy, interoperability, and equitable access to smart waste solutions [50].

The smart waste management market has experienced rapid growth in recent years, expanding from US$2.58 billion in 2024 to an estimated US$2.96 billion in 2025, with a CAGR of 14.5%. This growth stems from rising population levels, greater public awareness of environmental impacts, increased investments in waste management solutions, the expansion of recycling initiatives, and heightened concerns about public health. Smart waste management aims to transition from linear to circular systems by promoting the use of products that are upgradable, manufacturable, repairable, and recyclable [53]. This approach leverages IoT devices, sensors, and real-time monitoring systems to enhance operational efficiency, reduce costs, and minimize environmental impact. By enabling better resource allocation and supporting sustainable practices, it aligns with the goals of the circular economy. The market primarily includes smart collection, processing, disposal, and energy recovery. Smart collection, in particular, utilizes technologies such as sensors and automation to optimize waste collection through real-time data, digital platforms, and enhanced operational strategies.

Smart waste management systems integrate a range of technologies to enhance efficiency and sustainability. IoT-enabled bins equipped with sensors monitor waste levels, temperature, humidity, and composition, transmitting real-time data to centralized platforms. AI and machine learning algorithms analyse this data to forecast waste generation patterns, optimize collection schedules, and support long-term urban planning. GPS and smart routing systems utilize live traffic and bin data to optimize collection routes, thereby minimizing fuel consumption, traffic congestion, and vehicle wear and tear. Mobile applications keep residents informed about pickup schedules, recycling points, and waste sorting guidelines while allowing them to report issues such as overflowing bins or illegal dumping. At the processing stage, smart recycling facilities utilize robotics, optical sorters, and AI vision systems to automate and enhance waste sorting, thereby increasing the quality of recyclables and reducing reliance on manual labour [1, 12, 24].

These smart systems deliver significant benefits, including operational efficiency, cost reduction, and environmental protection. By leveraging real-time data, municipalities can enhance fuel efficiency, more effectively allocate labour resources, and increase vehicle utilization—ultimately reducing costs through fewer collections and lower maintenance demands. Environmentally, these systems reduce greenhouse gas emissions, enhance recycling rates, and lessen dependence on landfills. They also encourage public participation through transparency, gamification, and digital tools that build digital literacy. Moreover, smart waste management provides valuable data to guide evidence-based policymaking and ensure regulatory compliance. In doing so, it strengthens energy efficiency, promotes environmental safety in waste export processes, conserves resources, and improves overall quality of life [1, 12, 24].

Smart Waste Management Systems

Over the past decade, smart waste management systems have undergone significant transformation as cities increasingly adopt disruptive technologies to tackle the mounting challenges of urbanization, population growth, and environmental sustainability. Zhang and Kumar [55] describe a smart waste management system as a modern approach to urban waste handling that leverages smart technologies, such as sensors, the IoT, data analytics, cloud computing, Blockchain, robotic automation, and AI. These technologies work together to optimize every stage of the waste lifecycle, from generation and collection to sorting, recycling, and disposal, making the entire process more efficient and environmentally sustainable. Smart waste management systems utilize IoT-enabled sensors embedded in waste bins, collection trucks, and landfill sites to monitor fill levels, temperature, humidity, and location, transmitting real-time data via wireless networks such as GSM, LoRa, or NB-IoT. Authorities use this continuous data stream to analyze waste generation patterns and make informed decisions. Smart routing algorithms dynamically optimize collection schedules and vehicle routes, dispatching trucks only when bins near capacity, which reduces fuel consumption, vehicle wear, and labour hours while improving cost efficiency. Cloud-based analytics platforms aggregate sensor data to forecast waste trends, identify areas with high waste, and support long-term planning. Machine learning models predict equipment failures, enabling proactive maintenance, while deep learning architectures such as CNNs and a Visual Geometry Group 16-layer network (VGG16) automate waste classification and segregation to enhance recycling. Blockchain technology ensures transparency and accountability by recording waste transactions on immutable ledgers, while smart contracts automate payments and incentivize recycling. Additionally, waste processing facilities deploy robotic sorting systems with computer vision and machine learning to identify, pick, and separate recyclables more efficiently and safely than manual labour. Mobile and web applications keep citizens informed about collection schedules, facilitate reporting of overflowing bins, and promote recycling through gamification and rewards [37, 56].

An emerging trend involves integrating IoT, AI, Blockchain, and robotics into a unified smart waste management ecosystem. Together, these technologies form a closed-loop system that advances circular economy principles, minimizes reliance on landfills, and promotes sustainable urban development [56]. Sharma et al. [57] highlight that smart waste technologies reduce waste overflow, cut fuel consumption, and enhance service delivery in densely populated urban areas. These systems also promote environmental sustainability by increasing recycling rates, reducing illegal dumping, decreasing landfill dependency, and lowering greenhouse gas emissions. They generate valuable data that authorities can use to shape targeted waste reduction policies, monitor compliance with environmental regulations, and assess the effectiveness of implemented measures. As noted by Yusuf et al. [58] and Hussain et al. [51], smart waste management systems play a crucial role in promoting urban sustainability, improving public health, and enhancing resource efficiency. Figure 5 illustrates the conceptual model of a smart waste management system in smart cities.

Figure 5. Illustrates the conceptual model of a smart waste management system.

Components and Enabling Technologies of Smart Waste Management Systems

Smart waste management systems integrate various interconnected technologies to function as a unified and efficient system. Below is a brief explanation of how each component and technology function in the smart waste management systems.

Internet of Things (IoT) sensors

IoT sensors play a crucial role in smart waste management systems by continuously monitoring waste bins and collection points in real-time. They track fill levels, temperature, humidity, and hazardous gas emissions, supplying waste management operators with critical data to optimize routing and scheduling. By enabling dynamic collection schedules based on actual bin usage instead of fixed routines, these sensors help reduce operational costs and lower carbon emissions [59].

Artificial intelligence and machine learning

AI and machine learning are transforming waste management by analysing data from IoT sensors to predict waste generation patterns, optimize collection routes, and enhance recycling efforts. These technologies identify spatial and temporal waste trends, detect anomalies such as illegal dumping, and inform decisions that optimize resource allocation and management. Smart bins equipped with fill-level, odour, and material-recognition sensors collect detailed data, allowing AI to detect usage patterns across locations and demographics, such as increased waste in commercial areas during business hours and in residential zones during evenings and weekends. AI leverages these patterns to dynamically adjust collection schedules, reducing overflow and unnecessary pickups. Image recognition systems in sorting facilities automate waste segregation, improving recycling rates and minimizing human error [8, 60]. AI-powered route optimization further enhances efficiency by analysing real-time factors, such as traffic, bin status, vehicle capacity, and fuel usage, enabling dynamic rerouting that reduces emissions, travel time, and operational costs [22]. Cities using these systems report improved efficiency, lower congestion, and extended vehicle lifespan [12]. Predictive analytics, driven by historical and environmental data, helps forecast waste surges during festivals, seasonal shifts, or extreme weather events, allowing for proactive adjustments. Time-series forecasting models such as AutoRegressive Integrated Moving Average (ARIMA) and Long Short-Term Memory (LSTM) predict bin fill levels and support timely collections [8, 12, 22]. Demand forecasting, which utilizes data from sensors, social media, and demographic trends, enables waste managers to allocate resources precisely and plan for fluctuations [60]. Integrating AI into existing infrastructure requires planning for compatibility, training personnel, engaging stakeholders, and designing a scalable system that meets these requirements. Through real-time optimization and predictive modeling, AI enables more responsive, cost-effective, and sustainable waste management, supporting the achievement of circular economy goals and enhancing climate resilience [12].

Geographic information systems (GIS) and Global positioning systems (GPS)

GIS and GPS technologies combine spatial data with sensor inputs to enable accurate tracking and efficient routing of waste collection vehicles. GIS mapping identifies waste generation hotspots and highlights areas needing special attention, thereby informing data-driven decisions in urban planning and waste management. Meanwhile, GPS-enabled fleet management systems improve collection efficiency and reduce fuel consumption by delivering real-time navigation and traffic updates [61].

Cloud computing and Edge computing

Cloud computing platforms enable the storage, processing, and analysis of large volumes of data related to waste generated by IoT devices, supporting scalable and collaborative waste management through web and mobile applications. In tandem, edge computing processes data near its source, such as on-site IoT gateways, thereby minimizing latency and enabling faster, real-time decision-making, which is essential for time-sensitive tasks like hazardous waste monitoring [62].

Robotics and automation

AI-powered robotics is streamlining operations in sorting and treatment plants by automating labour-intensive tasks. Robotic arms equipped with AI now sort recyclables faster and more accurately than human workers, boosting throughput and minimizing workplace hazards. Additionally, autonomous waste collection vehicles and drones are expanding service coverage and enhancing safety by accessing previously inaccessible or hazardous areas [63].

Blockchain technology

Blockchain enhances transparency and traceability across the waste management supply chain by securely and immutably recording waste transactions, ensuring a clear audit trail. This technology improves accountability in tracking waste, verifying recycling certifications, and ensuring regulatory compliance. Pilot projects have demonstrated that Blockchain can reduce fraud and prevent illegal dumping by creating verifiable waste disposal records accessible to all stakeholders [11].

Smart waste bins and sensors

Smart bins are transforming urban waste collection by utilizing integrated sensors, such as ultrasonic, infrared, weight, and gas detectors, to monitor fill levels, detect odours and temperature changes, and identify hazardous materials. These IoT-enabled devices transmit real-time data to centralized municipal systems, allowing for dynamic and efficient management of waste collection. For instance, when a bin nears capacity, it automatically alerts collection services, enabling timely emptying and preventing overflow. This approach reduces unnecessary collection trips, cuts operational costs, and minimizes environmental impact from fuel consumption and vehicle emissions. In high-traffic areas, such as city centers and parks, odour sensors ensure that even nearly empty bins emitting unpleasant smells are serviced promptly, thereby maintaining public hygiene and satisfaction. AI and machine learning further enhance smart bin performance by analysing collected data to optimize collection routes and schedules [12, 64]. These technologies enable waste management services to concentrate resources on high-waste areas while reducing waste in low-use zones. This optimization is particularly beneficial for municipalities with tight budgets, as it reduces fuel consumption, minimizes vehicle wear and tear, and lowers labour costs. Cities that have adopted smart waste systems report reductions of up to 30% in fuel consumption and 20% in total driving distance, which directly translates into lower greenhouse gas emissions and improved environmental sustainability [8]. AI-driven decision-making ensures that only necessary trips are made, making waste management more efficient and eco-friendlier [60].

IoT communication networks

Reliable communication infrastructure plays a critical role in transmitting data from distributed bins to centralized control systems. Technologies such as LoRaWAN, NB-IoT, 5G, Wi-Fi, Zigbee, and mobile networks (4G/5G) support low-power, wide-area communication with minimal latency, ensuring robust and scalable connectivity even in densely populated urban environments. Among these, LoRaWAN stands out for its ability to transmit data over long distances using minimal power, making it especially suitable for cities where bins are widely spaced or where the power supply is limited. Li et al. [65] reported that LoRaWAN significantly reduced communication costs while enhancing the reliability of data transmission in smart waste systems. By enabling seamless and timely data flow, these communication networks ensure that information from all parts of the city reaches the central system without delays or data loss.

Centralized data management and analytics platforms

Sensor data are collected, aggregated, and analysed using cloud-based or edge computing platforms, where advanced analytics and machine learning algorithms identify fill patterns, optimize collection schedules, and detect anomalies such as illegal dumping or tampering with bins [66]. Once the data reaches the central system, AI and machine learning process it to uncover trends, such as areas with the highest waste generation or typical bin fill times, and use these insights to predict future waste levels and plan more efficient waste truck routes [67]. AI-driven route optimization has been demonstrated to reduce fuel consumption, lower worker stress, and expedite waste collection [57]. These systems can also trigger alerts in response to unusual patterns, allowing authorities to take quick action.

Smart collection vehicles

Modern waste collection fleets utilize GPS, RFID readers, and AI-driven route optimization systems to enhance efficiency and minimize environmental impact. Real-time data from smart bins directs vehicles along optimal routes, minimizing fuel consumption, avoiding traffic congestion, and shortening the time waste remains in public areas [68]. Managers can track trucks in real-time and quickly reroute them if a bin fills up unexpectedly. This flexibility enhances coverage of the high-waste regions and ensures timely pickups. According to Patel et al. [64], cities that adopted AI-based routing systems experienced faster collection times, lower fuel costs, and improved service. These smart trucks also send data back to the system, enabling continuous learning and optimization.

User engagement interfaces

Mobile applications and web portals play a crucial role in smart waste management systems by enabling residents, businesses, and city officials to monitor bin levels, track waste collection trucks, schedule pickups, and receive real-time alerts about issues such as overflowing bins. These user interfaces—whether in the form of mobile apps or computer dashboards—foster active citizen participation and encourage responsible waste disposal behaviour. For example, Singh et al. [69] developed an app that informed users about waste collection schedules, resulting in fewer missed pickups, reduced littering, and increased community involvement in maintaining a cleaner urban environment.

Integration with smart city platforms

Smart waste management systems play a key role in the broader smart city ecosystem by sharing data with other urban services. These systems connect with platforms responsible for traffic management, environmental monitoring, and emergency response, creating a networked infrastructure that facilitates real-time information exchange. By integrating waste management with other city functions, municipalities can promote sustainability and optimize resource use. This interconnected approach enables cities to respond more efficiently to changing conditions, reduce environmental impact, and make informed decisions that support long-term urban planning goals [36].

System Architecture for Smart Waste Management Systems

Smart waste management systems in smart cities are built on a layered architecture that includes sensing and data acquisition, communication, data processing and analytics, application and service, actuation and control, and security and privacy. Each layer supports specific functions essential to efficient waste management, which are described below.

Sensing and data acquisition layer

The perception layer, also known as the sensing and data acquisition layer, forms the foundation of smart waste management systems in smart cities by collecting real-time data from the physical environment. It connects the system to its surroundings through a network of interconnected sensors installed on waste bins, collection vehicles, and dumping sites. These sensors monitor key parameters, including bin fill levels, temperature, humidity, gas emissions such as methane or ammonia, and the presence of hazardous materials, utilizing technologies that include ultrasonic, infrared, weight, and gas sensors. By continuously capturing accurate data, the system stays responsive and data-driven [54, 62, 70]. The sensors transmit this information via wireless communication protocols, such as Zigbee, LoRaWAN, NB-IoT, or 5G, to centralized or distributed processing units, enabling real-time decision-making and predictive analytics. GPS modules on collection vehicles provide location data that optimizes routing and monitors vehicle performance. By converting the urban waste environment into actionable digital data, the perception layer enhances situational awareness, enables early detection of issues such as bin overflows or fires, and drives automation in waste handling. Its effectiveness directly impacts the system's overall efficiency, sustainability, and adaptability.

Communication layer

The communication layer connects key components, including sensors, smart bins, waste collection vehicles, and central monitoring platforms, through real-time data transmission. It reliably transmits information from distributed sensors, including fill levels, temperature, location, and bin status, to processing units for analysis and decision-making. To ensure seamless connectivity, this layer integrates various wireless and wired technologies, utilizing short-range protocols such as Zigbee, Bluetooth, and Wi-Fi for local networks, and long-range options including LoRaWAN, NB-IoT, LTE, and 5G for city-wide coverage [54, 70]. These technologies address specific needs for range, bandwidth, energy efficiency, and cost, with LoRaWAN and NB-IoT providing low-power, wide-area connectivity ideal for remote sensors. Vehicle-mounted gateways collect sensor data during waste collection rounds to enhance connectivity in hard-to-reach or densely populated areas. The communication layer supports two-way communication, enabling operators to send commands, adjust sensor settings, and optimize truck routes based on real-time data. It also manages data aggregation and routing to minimize latency and maximize bandwidth. Employing robust protocols and security measures safeguards data against loss, interference, and unauthorized access.

Data processing and analytics layer

The data processing and analytics layer receives, stores, and analyzes data from various sources, including IoT-enabled bins, GPS-equipped collection vehicles, and environmental sensors. This layer cleans, filters, and normalizes incoming data to ensure accuracy, then applies advanced techniques, such as statistical analysis, machine learning, predictive modeling, and deep learning (including CNNs and Transformers), to uncover patterns, predict waste generation, optimize routes, detect malfunctions, and classify waste for recycling [70-72]. It delivers these insights through dynamic dashboards and reporting tools that provide city managers, waste service providers, and policymakers with real-time system performance metrics. By transforming raw sensor data into actionable, predictive, and prescriptive information, this layer drives automation and strategic planning, helping cities reduce operational costs, minimize environmental impact, and improve service delivery, thereby establishing itself as a foundational element of intelligent waste management within the smart city ecosystem. Edge computing enables real-time anomaly detection, such as identifying fire hazards or illegal dumping, at the data source, thereby reducing latency and bandwidth usage. At the same time, cloud services manage big data analytics, route optimization, and integration with GIS for dynamic scheduling [17].

Application and service layer

The application and service layer interfaces directly with end-users, including municipal authorities, waste collection agencies, and citizens, by delivering intelligent services and applications that support real-time decision-making, operational efficiency, and user engagement. It hosts various tools that visualize sensor and IoT data from waste management infrastructure, such as dashboards for monitoring bin fill levels, route optimization for collection vehicles, and alert systems for maintenance and overflow events [54, 70]. By integrating advanced analytics and machine learning, this layer predicts waste generation trends and detects areas vulnerable to illegal dumping. It facilitates seamless communication among system components through standardized APIs and middleware, enabling interoperability with GIS, environmental monitoring platforms, and mobile apps. Users access real-time updates and submit requests via web portals or mobile apps, while AI-driven algorithms generate optimal collection routes that reduce travel time, fuel use, and emissions [51, 62, 70]. Beyond operational functions, the layer manages administrative tasks, including resource allocation, billing, and performance evaluation. It promotes community involvement by providing citizen-focused services, including pickup schedules, recycling tips, and gamified incentives. By combining user-centric design with intelligent service delivery, this layer enhances the responsiveness, transparency, and sustainability of urban waste management systems.

Actuation and control layer

The actuation and control layer forms the operational backbone of smart waste management systems by directly executing actions based on data analytics and sensor inputs from lower system layers. It converts digital decisions into physical operations, ensuring timely, efficient, and responsive waste collection, processing, and disposal. This layer comprises actuators and control units that interact with hardware components, including smart bins, collection vehicles, and processing facilities. For instance, smart bins equipped with fill-level sensors automatically trigger lid closures, compaction, or collection alerts when full [54, 70]. It also optimizes the routing and scheduling of collection trucks by sending real-time instructions based on traffic, bin status, and environmental conditions [51, 70]. Using embedded systems and programmable logic controllers (PLCs), this layer manages automated responses with minimal latency by interfacing with central platforms or edge devices, thereby enhancing responsiveness and reliability, which are critical to urban public health and environmental sustainability. Furthermore, it dynamically adapts operations to changing conditions, such as waste surges, equipment failures, or shifting collection priorities, continuously aligning activities through real-time communication and feedback loops with municipal goals, including energy efficiency, reduced emissions, and improved citizen satisfaction.

Security and privacy layer

This layer is crucial in safeguarding the integrity, confidentiality, and availability of data in smart waste management systems by ensuring that only authorized entities access or manipulate sensitive information, including sensor readings, user identities, location, and operational data. It employs robust encryption techniques to protect data both in transit and at rest across system components, including smart bins, IoT gateways, cloud servers, and mobile applications, thereby preventing interception or tampering by malicious actors. The system verifies user and device identities through authentication and authorization mechanisms that enforce access control based on predefined roles and privileges. To maintain trust and accountability, it continuously monitors and audits system activity, detecting anomalies and generating alerts for suspicious behaviour, thus enabling real-time incident response and forensic analysis. Furthermore, it prioritizes privacy by applying techniques like data anonymization and differential privacy, protecting personally identifiable information while still supporting data-driven insights and analytics. Figure 6 illustrates the primary layers of the system architecture for smart waste management systems in smart cities.

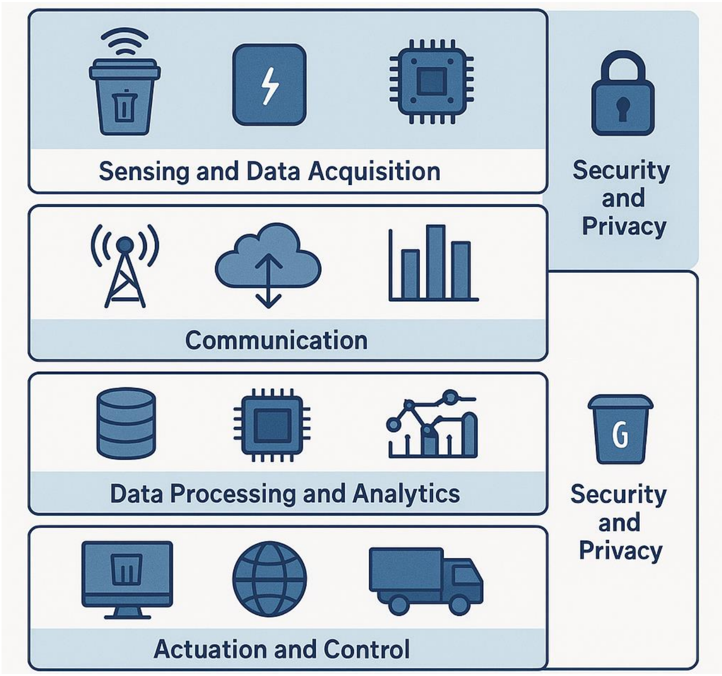

Figure 6. Illustrates the primary layers of the system architecture for smart waste management systems in smart cities.

Benefits of Smart Waste Management Systems

Smart waste management systems utilize advanced technologies, including IoT, data analytics, and automation, to deliver numerous benefits. Table 1 provides brief descriptions of the benefits of smart waste management systems.

Table 1. Brief descriptions of the key benefits offered by smart waste management systems in smart cities.

S/No	Benefits	Brief Description	References
1	Improved efficiency in waste collection	Smart waste management systems use real-time data from IoT-enabled sensors embedded in bins to monitor fill levels and trigger collections only when necessary. This approach reduces truck trips by up to 30%, lowers fuel consumption, and cuts operational costs. By integrating real-time analytics and AI-driven algorithms, these systems transmit data to centralized platforms that dynamically schedule pickups and optimize routes based on bin status, traffic conditions, and vehicle capacity, achieving up to 32% greater route efficiency and 29% reductions in fuel use and emissions compared to traditional methods. Multiagent simulations and field tests demonstrate that data-driven collection strategies	[31, 42, 73]

		outperform fixed schedules by increasing public satisfaction, reducing employee workload, and improving environmental outcomes. These systems also enhance resource allocation, minimize equipment wear, and enable cities to adapt quickly to changing waste patterns, resulting in cleaner environments, cost savings, and more sustainable urban operations.	
2	Reduction of environmental impact	Smart waste management systems reduce environmental impact and promote sustainability in smart cities by leveraging IoT, AI, and advanced analytics to optimize waste collection, processing, and disposal. These systems utilize sensor-equipped bins and dynamic route optimization algorithms to minimize the number of collection trips, resulting in a significant reduction in fuel consumption and greenhouse gas emissions. Pilot studies have shown up to a 29% reduction in emissions and a 32% increase in route efficiency compared to traditional methods. AI-powered sorting and predictive analytics increase recycling rates and reduce landfill dependency, supporting circular economy practices. By ensuring timely waste removal, these systems enhance urban hygiene, reduce littering, and protect public health and ecosystems. Multiagent simulations and field experiments consistently demonstrate that sensor-driven, data-informed approaches outperform conventional methods in terms of environmental preservation, operational efficiency, and user satisfaction. Additionally, integrating Blockchain and secure data standards enhances transparency, traceability, and regulatory compliance. Together, these innovations enable cities to lower their carbon footprints, conserve resources, and build cleaner, greener urban environments.	[23, 42, 73]
3	Cost savings for municipalities	Smart waste solutions enable municipalities to reduce labour, fuel, and vehicle maintenance costs by preventing bin overflow and damage, thereby extending the lifespan of containers. By integrating IoT sensors, real-time data analytics, and route optimization algorithms, these systems streamline waste collection and processing through dynamic scheduling based on actual bin fill levels. This reduces unnecessary trips, cuts fuel consumption, and lowers operational expenses—pilot studies show up to a 32% boost in route efficiency, a 29% drop in fuel use and emissions, and an 18% reduction in vehicle maintenance. IoT-enabled smart bins and automated alerts ensure timely waste removal, avoiding costly overflows and emergency cleanups. Municipalities utilize data-driven insights to allocate resources more efficiently, optimize bin placement, and increase recycling rates, ultimately reducing costs and expenses. Additionally, digital twins and AI technologies offer predictive analytics that support proactive planning and enhance cost savings. Together, these innovations improve service quality and sustainability while providing	[21, 42, 73]

		scalable and replicable models for cities seeking to optimize both economic and environmental benefits.	
4	Enhanced recycling rates	Smart waste management systems, driven by IoT sensors, AI, robotics, and advanced data analytics, enhance recycling rates and reduce environmental impact in sustainable smart cities. These systems utilize AI-powered sorting technologies and sensor-equipped smart bins to separate recyclables from general waste, thereby minimizing contamination and enhancing recycling efficiency. Real-time monitoring and data collection enable dynamic waste collection and efficient source-level sorting, which improves the quality of recovered materials. In recycling facilities, AI and robotic automation streamline material identification and separation, boosting recovery rates and reducing reliance on manual labour. Compact terahertz devices further improve plastic sorting accuracy in public pre-sorting, easing the workload on recycling centers. Integrated logistics and predictive analytics optimize collection routes and schedules, decreasing landfill use and maximizing resource recovery. Studies show that these innovations can increase recycling rates by 10–30%, enhance sorting efficiency by up to 18%, and lower operational costs, highlighting their vital role in promoting a circular economy and urban sustainability.	[8, 21, 73-75]
5	Real-time data analytics and monitoring	Smart waste management systems use IoT sensors and real-time dashboards to monitor waste levels, contamination, and collection status, enabling timely interventions and informed planning. Sensors embedded in bins and collection vehicles transmit continuous data on fill levels, waste types, and locations to centralized platforms for immediate analysis and processing. Advanced analytics, including machine learning and predictive modeling, process this data to forecast trends, optimize collection routes, and schedule pickups efficiently, thereby reducing unnecessary trips, lowering operational costs, and minimizing environmental impact. Automated alerts notify municipal authorities when bins approach capacity, ensuring prompt collection and preventing overflows and health risks. These systems also enable automated waste segregation, boost recycling rates, and provide critical insights for resource allocation and urban planning. Pilot projects have demonstrated 99% accuracy in predicting bin status, resulting in a 32% increase in route efficiency and a reduction of up to 29% in fuel use and emissions. Through real-time dashboards and mobile apps, both authorities and citizens can monitor bin status, receive alerts, and engage in the waste management process, strengthening transparency and public trust. By supporting dynamic, data-driven decisions, these technologies make waste management more proactive, efficient, and sustainable.	[25, 42, 75, 76]
6	Improved public	Smart waste management systems enhance public health and sanitation in sustainable smart cities by using real-time	[51, 54]

	health and sanitation	monitoring, IoT-enabled bins, and intelligent data analytics. These systems prevent bin overflow and ensure timely waste collection, reducing the duration waste remains uncollected and lowering the risks of pest infestations, foul odours, and related health hazards. Sensor-equipped bins and automated alerts trigger swift waste removal, while live data streams and web interfaces allow municipal authorities to monitor conditions and respond quickly to emerging sanitation issues. Advanced technologies, such as multi-objective intelligent systems, track environmental factors like air and water quality and detect sanitation concerns with high accuracy. Simulation studies and field experiments demonstrate that smart systems outperform traditional methods by enhancing collection efficiency, reducing staff workload, and increasing public satisfaction with urban cleanliness. Together, these innovations foster cleaner, safer, and healthier cities, supporting both immediate public health and long-term sustainability.	
7	Citizen engagement and awareness	Smart waste management systems foster sustainable behaviors and active citizen engagement by integrating technology with community-focused strategies. Mobile apps provide residents with real-time updates on collection schedules, recycling guidelines, and reward programs, encouraging responsible waste disposal. IoT-enabled smart bins and user-friendly platforms allow users to monitor bin status, track collections, and understand their environmental impact. Yogyakarta's smart city initiatives demonstrate that combining advanced sensors, data analytics, and targeted educational campaigns enhances public participation, particularly during critical events such as landfill closures. Reward-based programs and citizen science projects further motivate involvement by reframing waste as a valuable resource. Research highlights that digital platforms and awareness campaigns are crucial in developing informed, proactive citizens who support effective municipal waste strategies. By engaging stakeholders and raising civic awareness, smart systems enhance collection efficiency, optimize resource utilization, and foster long-term urban sustainability, empowering communities to take ownership of their environment.	[54, 77]
8	Scalability and flexibility	Smart waste management systems provide scalable, flexible solutions that cities of all sizes can adopt and tailor to various waste types, including industrial, medical, and organic waste. By leveraging IoT sensors, edge computing, and cloud-based analytics, these systems seamlessly expand across neighbourhoods and cities, accommodating new waste streams and sensor technologies. Modular architectures integrating federated learning, Blockchain, and decentralized applications ensure secure data handling and efficient operations as systems scale. AI-powered route optimization and real-time monitoring enable cities to adjust	[22, 25, 42, 78]

		collection schedules and routes based on actual demand, reducing costs and environmental impact. Real-world implementations demonstrate that these systems can process millions of data points, increase route efficiency by over 30%, and reduce fuel consumption and emissions by nearly 30%. Their adaptability allows municipalities to tailor solutions to local needs and integrates them with broader smart city initiatives, positioning smart waste management as a key component of sustainable, data-driven urban development.	
9	Reduction of illegal dumping and littering	Smart cities utilize advanced waste management systems, powered by technologies such as IoT sensors, deep learning, and real-time monitoring, to effectively reduce illegal dumping and littering. These systems, equipped with visual recognition and cognitive computing frameworks, automatically analyze video feeds from city surveillance cameras to detect unauthorized waste disposal in public spaces. Deep learning models, such as the Single Shot MultiBox Detector (SSD), MobileNet v2, and YOLOv8, accurately identify bulky waste in restricted areas and trigger instant alerts, enabling municipal authorities to respond swiftly. This proactive approach deters offenders, streamlines enforcement, and optimizes resource deployment, resulting in cleaner urban environments. Cloud-based and edge computing solutions ensure scalability and seamless integration with other municipal services, supporting comprehensive environmental management. Field studies and simulations demonstrate that intelligent systems consistently outperform traditional methods in maintaining public cleanliness and safety. By implementing these technologies, smart cities enhance compliance, reduce environmental risks, and promote sustainable urban living.	[50, 79]
10	Integration with circular economy models	Smart waste management drives circular economy initiatives by providing accurate data on waste composition, which enhances material recovery and reuse in industries such as manufacturing and construction. Transforming traditional linear waste systems into closed-loop processes promotes resource efficiency, reduces waste, and strengthens environmental sustainability. Technologies such as IoT, machine learning, and Blockchain enable real-time tracking, automated sorting, and transparent data sharing, all of which enhance recycling, reuse, and material recovery. These innovations streamline waste collection, boost sorting efficiency, and help identify valuable materials within waste streams, thus minimizing landfill use and advancing the 4Rs—Reduce, Reuse, Recycle, and Recover. Circular economy integration also fosters collaboration among citizens, governments, and industries, supporting eco-friendly business models, improving social well-being, and driving climate action by lowering carbon emissions. City-level initiatives such as composting, biogas production, and	[80]

	upcycling further reduce carbon footprints and promote sustainable urban development. Blockchain frameworks enhance traceability, ensure accountability, and encourage citizen participation through reward systems, building trust and engagement in circular practices.

BLOCKCHAIN, IoT, AI, AND ROBOTICS IN EFFICIENT WASTE MANAGEMENT

Blockchain in Smart Waste Management

Blockchain technology is transforming smart waste management systems. Blockchain operates as a decentralized and distributed digital ledger that securely records transactions in a transparent and tamper-resistant manner [48, 81, 82]. It organizes transaction data into blocks, each linked chronologically to the previous one, forming a continuous chain. Once the network adds a block to the chain, altering its contents becomes extremely difficult without modifying all subsequent blocks and obtaining consensus from the entire network. Blockchain technology employs a Peer-to-Peer (P2P) architecture to store and process data in a secure, transparent, reliable, and trustworthy manner. It incentivizes miners to validate transactions and create new blocks through consensus algorithms such as Proof-of-Work (PoW), Proof-of-Stake (PoS), and Proof-of-Authority (PoA), which ensure agreement across distributed nodes and prevent unauthorized transactions. Blockchain platforms can be permissionless and permissioned. Permissionless Blockchains, such as Ethereum, are open and allow public access to transaction data, enabling the digitization of assets and tracking through smart contracts. In contrast, permissioned Blockchains, such as Hyperledger Fabric and Quorum (based on Ethereum), restrict access to designated organizations, ensuring privacy and security [48, 81, 82].

Although Blockchain offers significant potential for waste management, its widespread adoption encounters several obstacles. High energy consumption, scalability limitations, and a general lack of stakeholder awareness hinder its integration into existing systems. Additionally, current regulatory frameworks often struggle to accommodate decentralized technologies, further complicating implementation efforts. Researchers are addressing these challenges by developing lightweight consensus algorithms and exploring hybrid Blockchain architectures. These innovations aim to strike a balance between decentralization, sustainability, and cost-efficiency, making Blockchain more practical for real-world waste management applications [83]. Smart contracts, embedded programs within the Blockchain, automate and enforce agreements among stakeholders in waste management. These contracts register participants, issue certificates, and perform essential tasks such as waste tracking and identity management. The Blockchain securely stores encrypted data in an immutable, chronological ledger, ensuring provenance of waste. This enables authorities to monitor regulatory compliance, reward responsible citizens, and identify non-compliant handlers—all while preserving user anonymity. By maintaining a decentralized ledger (a distributed database that records transactions across multiple independent nodes without depending on a central authority) that records the origin, movement, and disposal of waste, Blockchain enhances traceability, promotes accountability, and supports regulatory enforcement. Smart contracts automatically trigger payments for collection or recycling services when predefined conditions are met, reducing errors and enhancing operational efficiency. Through token-based incentives, citizens receive rewards for proper waste disposal, which they can exchange for goods and services. This decentralized approach empowers citizens, local authorities, and companies to collaborate through transparent data sharing and automated interactions, creating a robust platform for urban waste management [25, 26, 39, 40].

Blockchain technology is revolutionizing waste management by providing secure, transparent, and decentralized solutions that enhance traceability, efficiency, and accountability. Stakeholders can track waste in real time from its generation to final disposal, leveraging the immutable ledger to ensure data integrity. Smart contracts automate transactions, enforce regulatory compliance, and manage waste processing tasks, thereby reducing administrative costs and enhancing operational workflows. Furthermore, these contracts support incentive mechanisms, such as token-based rewards, that motivate households and businesses to participate in recycling and waste segregation. When integrated with AI and IoT, Blockchain optimizes waste collection routes, monitors recycling activities, and supports data-driven decision-making by securely storing and analysing real-time operational data. This integration fosters transparent, collaborative ecosystems in cities and industries that promote circular economy practices and minimize environmental impact [16, 19, 26, 81, 84, 85].

Recent studies on smart waste management in cities have utilized diverse blockchain platforms to optimize specific functions, including waste classification, route planning, traceability, and incentivization. Researchers have leveraged Ethereum to automate and secure waste management transactions, including traceability, payments, and social crypto-coin reward systems for municipal waste collection [26]. Custom NFT platforms, such as TrackGenesis NFT and OpenSea.io, have facilitated e-waste management by enabling the traceability and trading of waste-related assets [86]. Polkadot, using the Substrate framework, has supported hybrid blockchain solutions for supply chain tracking, incentivization, and gamification in waste management [24, 26]. Additionally, both general and private blockchain networks have provided secure and transparent data storage, as well as executed smart contracts across various waste management applications [7, 19, 25, 26, 87].

Beyond municipal waste management, Blockchain effectively addresses specialized sectors such as e-waste and healthcare waste. It enables the precise tracking and categorization of waste types, verifies handlers' credentials, and securely stores critical documents, such as weighing vouchers and transport logs. Technologies such as RFID, NFC, and QR codes assign unique digital identifiers to waste, which the Blockchain records for real-time tracking throughout the supply chain. This prevents data tampering and fraud, facilitates continuous monitoring, and ensures strict regulatory compliance. By enabling peer-to-peer data sharing among authorized stakeholders, Blockchain breaks down data silos and fosters transparency across the waste management network. Additionally, Blockchain-based incentive programs for e-waste collection have boosted recycling rates and reduced landfill waste, demonstrating the technology's practical benefits in specialized waste sectors [7, 88].

Blockchain technology transforms smart waste management by boosting efficiency, transparency, and accountability. Its decentralized, tamper-resistant ledger securely records and shares waste-related data across a wide range of stakeholders, including waste generators, collectors, recyclers, regulatory bodies, and consumers [89]. Table 2 provides a brief description of the key roles Blockchain plays in the domain of waste management.

Table 2. Summary of key roles Blockchain plays in the domain of waste management

S/No	Roles	Brief Description	References
1	Enhancing transparency and traceability	Blockchain enhances transparency, traceability, and accountability in smart waste management by securely recording every stage of the waste lifecycle—from generation and collection to transportation, recycling, and disposal—on an immutable, decentralized ledger. By integrating real-time data from IoT-enabled sensors, stakeholders can monitor waste status and movement, ensuring compliance with environmental regulations while deterring illegal dumping and misreporting. Smart contracts automate tasks such as verifying waste sorting, scheduling collections, conducting compliance checks, and distributing rewards, thereby boosting operational efficiency and responsibility. Each waste item carries a unique identifier that tracks its origin, composition, handling, and final treatment method. Authorized users, including regulators and the public, access this information through decentralized applications, fostering trust, enhancing decision-making, and promoting circular economy efforts. Additionally, Blockchain protects sensitive data through encryption and secure standards, making it a powerful tool to build sustainable, transparent, and compliant waste management systems in smart cities.	[25, 90]
2	Improving efficiency through smart contracts	Smart contracts automate and streamline key processes in the waste management sector, boosting efficiency and sustainability in smart cities. They trigger payments to waste collectors upon verified pickups and reward households with tokenized incentives for proper waste segregation. By minimizing administrative overhead, reducing human error, and enabling real-time scheduling, dynamic route optimization, and automated compliance checks, smart contracts eliminate delays and reduce the need for manual intervention. IoT sensors in waste bins transmit data to edge gateways, which securely record the information on the Blockchain. Smart contracts then activate waste collection only when bins are full, optimizing truck routes and lowering fuel consumption and operational costs. This automation ensures timely service delivery, tamper-proof record-keeping, and improved communication among stakeholders, fostering trust and	[25, 91]

		accountability. In e-waste management, smart contracts facilitate coordination among producers, recyclers, and regulators to enforce compliance with predefined rules at every stage, thereby enhancing regulatory oversight and operational efficiency. Simulation studies confirm that Blockchain-based smart contracts deliver more reliable, responsive, and accessible waste management services in smart city environments. By integrating these technologies, cities can reduce costs, support data-driven decision-making, and implement scalable, sustainable waste management solutions that are effective and efficient.	
3	Enabling decentralized waste trading platforms	Blockchain technology powers decentralized marketplaces that enable secure, transparent, and intermediary-free trading of recyclable materials and waste-derived resources. These platforms directly connect waste producers with collectors, recyclers, and buyers, streamlining material recovery and advancing circular economy practices. Smart contracts automate and immutably record transactions, ensuring trust, accountability, and faster settlements. For example, platforms on the Binance Smart Chain use smart contracts to facilitate direct trading of waste assets while maintaining transparency. In e-waste management, Blockchain systems integrate IoT sensors and user authentication to track waste deposits, automate reward distribution, and securely document trading activities, thereby promoting responsible recycling. Token-based rewards incentivize proper disposal, while material tracking throughout the lifecycle enhances traceability. By reducing fraud, cutting operational costs, and boosting transparency, Blockchain creates a collaborative, tamper-proof waste trading ecosystem. It also empowers communities, especially those with limited infrastructure, to organize local waste collection and recycling efforts and trade recyclables directly, supporting sustainable, community-driven waste management.	[7, 19]
4	Strengthening data security and privacy	Blockchain technology strengthens data security, privacy, and efficiency in smart waste management by leveraging its decentralized, immutable, and transparent architecture. It secures sensitive data, such as household waste patterns, corporate waste volumes, user identities, and business transactions, through cryptographic methods, advanced encryption standards, and integration with IoT devices and distributed storage systems, including the InterPlanetary File System (IPFS). The system grants access and modification rights only to authorized parties while maintaining a fully auditable trail of changes, thereby enhancing trust and enabling evidence-based policymaking. Smart contracts automate key processes such as payments for waste collection and enforcement of compliance-based incentives or penalties, promoting fairness and minimizing the need for intermediaries. Additionally, technologies such as federated learning and differential privacy enable stakeholders to perform collaborative analytics without revealing raw data. Together, these features enhance data protection, prevent fraud, ensure regulatory compliance, and support scalability, positioning Blockchain as a reliable and scalable solution for sustainable smart cities.	[25, 29, 85]

5	Supporting regulatory compliance and auditing	Regulatory agencies can leverage Blockchain's transparent and immutable record-keeping to conduct real-time audits and enforce waste management standards more efficiently. By automating reporting processes, Blockchain eliminates much of the manual documentation and simplifies compliance with waste disposal regulations and emission limits. Its decentralized ledger tracks every stage of the waste lifecycle—from generation and collection to transportation, recycling, and disposal—providing all stakeholders with real-time access to accurate, tamper-proof data. This traceability enables regulators to quickly detect and prevent illegal dumping, misreporting, or fraud. Smart contracts enhance compliance by embedding legal and policy requirements directly into the system, executing only compliant transactions and triggering alerts or penalties when violations occur. In specialized areas, such as e-waste, Blockchain platforms can enforce specific regulations and create auditable transaction trails. This high level of transparency reduces administrative burdens, streamlines reporting, and builds trust among regulators, businesses, and the public.	[7, 40]

IoT in Smart Waste Management

The rapid advancement of IoT-based smart technologies is transforming urban waste management by enabling real-time monitoring, facilitating data-driven decision-making, and automating operations to address key challenges effectively. The IoT is a network of interconnected physical devices, such as sensors, appliances, vehicles, actuators, communication systems, and industrial machines, that use standardized protocols to collect, exchange, and process data over the Internet or other communication networks [92-95]. It facilitates interactions not only between humans but also between humans and machines, as well as among machines themselves, to support efficient, energy-saving, safe, and environmentally friendly management, control, and operation [96]. By integrating application solutions with communication technologies, such as identification and tracking systems, sensor networks, wired and wireless actuators, improved communication protocols, and distributed intelligence, IoT enhances automation and decision-making capabilities [96].

Smart waste management systems utilize IoT technology to connect a range of devices, including smart bins, sensors, actuators, and network gateways, which collect and transmit data on waste levels, bin occupancy, environmental conditions, and the locations of collection vehicles [97]. Technologies such as RFID tags, sensors, actuators, wireless sensor networks, near-field communication, and GPS enable the annotation and transmission of critical information. An IoT-enabled waste management system typically comprises three main layers: perception, network, and application. The perception layer features smart waste bins equipped with ultrasonic, weight, and gas sensors that monitor fill levels, detect hazardous gases, and track bin weight, generating continuous data streams. The network layer enables low-power, long-range communication between edge devices and cloud servers using wireless technologies such as LoRaWAN, Zigbee, NB-IoT, and 5G. The application layer processes this data to deliver actionable insights for municipal authorities and waste collection agencies. By integrating IoT technology into waste bins, treatment stations, transportation trucks, storage facilities, and inspection drones, municipalities can monitor all stages of waste management in real-time. This connectivity enables authorities to optimize collection routes, prevent environmental hazards, and make informed, data-driven decisions promptly. Ultimately, the deployment of sensors and IoT devices across the waste management chain enhances operational efficiency and promotes effective resource recycling [96, 98].

Intelligent waste monitoring platforms leverage data analytics, machine learning, and IoT technologies to enhance the efficiency, sustainability, and cost-effectiveness of waste management. These systems dynamically optimize collection routes based on real-time bin occupancy, reducing fuel consumption, operational costs, and carbon emissions [70]. IoT-enabled sensors continuously monitor bin fill levels and trigger alerts when thresholds are reached, ensuring timely collection and preventing overflow. By facilitating predictive maintenance, these systems also improve service reliability and reduce equipment downtime [17]. Integrating IoT with AI and Blockchain further strengthens security, transparency, and data sharing across stakeholders [99]. AI helps predict waste generation trends and recommend sustainable policies, while automated segregation systems, utilizing sensors and image processing, classify waste into recyclable and non-recyclable categories, thereby improving recycling efficiency. Additionally, IoT tools monitor emissions such as carbon dioxide and methane, supporting broader environmental monitoring efforts. Smart waste management systems reduce landfill dependency, lower health risks associated with pests and odours, and decrease labour, fuel, and equipment costs by streamlining operations and resource allocation.

The IoT is transforming waste management by enabling real-time monitoring, data collection, and intelligent decision-making. IoT-based systems provide dynamic solutions by utilizing smart bins equipped with sensors. These sensors monitor fill levels, sort waste by weight, and transmit data to centralized platforms through networks such as Wi-Fi, cellular, LoRaWAN, or NB-IoT. The collected data enables municipalities to optimize their collection routes, reduce fuel consumption, lower operational costs, and minimize carbon emissions. Technologies such as ultrasonic and weight sensors ensure accurate tracking of bin status and waste categorization, while GPS-enabled collection vehicles contribute to operational transparency and enhanced route efficiency. Mobile applications and user-friendly interfaces also enhance citizen engagement by promoting active participation in cleaner and more sustainable waste practices [22, 25, 60, 100]. The integration of IoT into waste management supports the development of sustainable and resilient smart cities. By analysing real-time and historical data, city authorities can better forecast waste generation patterns, tailor collection schedules, and allocate resources more effectively. Predictive analytics powered by AI and ML—often embedded in platforms like Google Maps—enable more efficient routing and scheduling. These insights help reduce unnecessary trips, limit environmental degradation, and support circular economy strategies that encourage the reuse and recycling of waste. Furthermore, IoT applications extend across the entire waste lifecycle from generation and sorting to transportation, disposal, and reuse streamlining operations while improving energy efficiency, governance, and cost-effectiveness [8, 10, 101-103].

Studies have shown measurable improvements in waste collection efficiency, environmental outcomes, and public health through the adoption of IoT. As urban populations continue to grow, the need for effective waste management systems becomes increasingly pressing. By embracing IoT, cities can not only modernize their waste infrastructure but also lay the foundation for long-term sustainability, efficient resource utilization, and enhanced quality of urban life. By enabling real-time monitoring, data-driven decision-making, and optimized resource utilization, IoT enhances waste management efficiency and supports the broader objectives of smart city development. Table 3 provides a brief description of the key roles of IoT in modernizing waste management practices and advancing the goals of smart city development.

Table 3. Summary of key roles IoT plays in the domain of waste management.

S/No	Roles	Brief Description	References
1	Real-time monitoring & dynamic collection	IoT plays a vital role in smart waste management by enabling real-time monitoring and dynamic collection of waste through sensors such as ultrasonic, infrared, or weight-based devices. These sensors continuously track bin fill levels and environmental conditions, transmitting data wirelessly to centralized platforms or cloud databases. Municipal authorities utilize this information to monitor thousands of bins and vehicles, receive automated alerts for issues such as overflows or gas leaks, and adjust collection schedules based on the actual status of each bin, rather than fixed routes. This dynamic approach reduces unnecessary trips, fuel use, operational costs, traffic congestion, and carbon emissions. Advanced systems integrate GPS and communication technologies, such as GSM and LoRaWAN, to support accurate location tracking and efficient route planning. Dashboards and mobile applications deliver live updates to both officials and citizens, increasing transparency and community engagement. Experimental and simulation studies consistently demonstrate that IoT-based dynamic waste collection minimizes overflow, improves resource allocation, and enhances public satisfaction, thereby contributing to cleaner, more sustainable, and liveable smart cities.	[104, 105]
2	Data-driven decision making	IoT systems generate vast datasets on waste generation patterns across regions and timeframes, which advanced analytics and machine learning algorithms use to predict trends and optimize resource allocation. By deploying sensors in waste bins and collection points, these systems gather real-time data on waste levels, types, and environmental conditions, which they transmit to cloud or edge platforms for immediate analysis. Models such as random forest (RF) and ARIMA enable accurate predictions	[24, 25]

		of waste accumulation, support dynamic scheduling, and optimize collection routes. This allows authorities to anticipate bin overflows, adjust collection frequency based on demand, and minimize unnecessary trips, thereby reducing fuel consumption and environmental impact. These intelligent platforms also provide real-time alerts and decision support to drivers, dispatchers, and citizens, enhancing transparency and operational responsiveness. In e-waste management, combining IoT data with machine learning supports precise sorting and resource recovery, contributing to sustainability goals. Empirical studies and real-world prototypes consistently demonstrate that IoT-enabled, data-driven systems outperform traditional fixed-schedule methods in terms of accuracy, efficiency, and user satisfaction, positioning them as essential tools for building innovative, sustainable urban environments.	
3	Enhanced citizen engagement	Modern IoT-based waste management systems engage citizens through mobile apps and web portals that deliver real-time updates on bin status, collection schedules, and environmental metrics. These platforms empower residents to receive alerts, report overflowing bins or illegal dumping, and track their waste generation, promoting accountability and encouraging waste reduction efforts. By enabling two-way communication, IoT systems connect households, waste collectors, and disposal sites within a transparent digital network, allowing residents to submit feedback, make service requests, and contribute to community-driven improvements. This engagement enhances public awareness, improves waste sorting habits, and boosts satisfaction with municipal services. Additionally, data from IoT systems supports educational campaigns and reward-based initiatives, strengthening citizen participation in sustainability. Ultimately, IoT-driven engagement fosters cleaner, more efficient, and inclusive smart cities.	[8, 54]
4	Integration with smart city infrastructure	IoT-enabled waste management systems integrate into smart city ecosystems by connecting smart bins, collection vehicles, traffic systems, and central monitoring platforms. Sensors installed in bins continuously track fill levels and environmental conditions, transmitting real-time data via networks such as LoRaWAN or Wi-Fi. Municipal authorities utilize this data to optimize operations by dynamically adjusting collection routes based on the current bin status and traffic conditions, thereby reducing fuel consumption, operational costs, and environmental impact. Integration with data analytics platforms, cloud computing, and citizen-facing apps further enhances decision-making, transparency, and public engagement. This interconnected infrastructure allows stakeholders to share data efficiently, allocate resources effectively, and respond swiftly to issues such as bin overflows or illegal dumping.	[106]
5	Maintenance and operation	IoT devices monitor the operational status of collection vehicles and waste processing equipment, utilizing sensor-informed algorithms to detect early signs of failure and enable predictive maintenance, thereby reducing downtime and repair costs.	[42, 91]

	al efficiency	Smart bins equipped with sensors automatically report mechanical issues, battery levels, and malfunctions, ensuring reliable service. These bins also track fill levels and environmental conditions, transmitting real-time data via LoRaWAN or cellular networks to centralized cloud platforms for analysis and monitoring. This data-driven system enables dynamic route optimization, dispatching collection vehicles as needed, thereby reducing travel distances, fuel consumption, and emissions. Pilot studies have shown up to a 32% improvement in route efficiency and a 29% reduction in fuel use compared to traditional methods. IoT systems detect equipment wear and anomalies, prompting timely interventions that lower maintenance costs by up to 18%. Automated alerts and intelligent scheduling minimize manual oversight, prevent bin overflows, reduce labour costs, and promote cleaner urban environments, ultimately leading to higher public satisfaction. Integration with smart traffic systems and energy-efficient algorithms further enhances operational efficiency, extends sensor lifespans, and reduces errors, positioning IoT-enabled waste management as a cornerstone of sustainable, intelligent cities.	
6	Smart bins	Smart bins are modernized garbage containers equipped with IoT technology that enables them to monitor fill levels, track usage, and, in some cases, compress waste to boost capacity. Many solar power installations are being made, making them more sustainable. When they approach full capacity, they automatically notify a control centre to schedule a pickup. Cities like Barcelona and Seoul have adopted smart bins to reduce unnecessary collection trips and prevent overflowing, resulting in cleaner streets and increased resident satisfaction.	[107]
7	Waste tracking	The IoT streamlines waste tracking and improves accuracy by using GPS and RFID tags on garbage trucks and waste containers. These devices enable real-time monitoring, ensure timely collection, and prevent missed bins. They also help enforce the safe and proper handling of hazardous or medical waste. When a truck strays from its designated route or an irregularity occurs, the system instantly issues an alert.	[108]
8	Route optimization and efficient use of resources	IoT enhances waste management by using real-time and historical data to optimize collection routes and schedules, helping cities save time, fuel, and money. Smart systems recommend efficient collection plans, avoid empty bins, and bypass congested areas, thereby reducing fuel consumption, lowering emissions, and extending the lifespan of waste trucks and bins. One study showed that cities implementing IoT and edge computing solutions reduced operational inefficiencies by 25%.	[25]

Artificial Intelligence in Smart Waste Management

Artificial intelligence is enhancing efficiency, sustainability, and operational intelligence in smart waste management systems. Traditional approaches often struggle with issues such as irregular collection schedules, overflowing bins, high operational costs, and low recycling rates. By leveraging AI technologies, cities and municipalities can automate processes and make informed, data-driven decisions to effectively overcome these challenges. Artificial Intelligence is a field of computer science that develops systems designed to perform tasks that typically require human intelligence [82, 95, 109, 110]. It encompasses tasks such as reasoning, learning from experience, decision-making, understanding natural language, pattern and image recognition, and adapting to new environments or inputs. The key subfields of AI include machine learning, which allows computers to learn from data without explicit programming through supervised, unsupervised, and reinforcement learning. Deep learning, a subset of machine learning, uses artificial neural networks to automatically extract patterns and representations from large datasets through multiple computational layers. Natural language processing enables machines to understand, interpret, and generate human language, supporting applications like translation, sentiment analysis, and chatbots. Computer vision allows systems to interpret visual inputs and make informed decisions based on images, as seen in applications such as facial recognition and object detection. Expert systems replicate human decision-making by applying logical rules to a knowledge base, commonly supporting diagnostics and analysis in healthcare and engineering [18, 111].

AI enhances waste management by leveraging large volumes of sensor and historical data to forecast waste generation patterns, enabling dynamic route optimization for collection vehicles and thereby reducing fuel consumption and carbon emissions. Through predictive analytics, AI minimizes unnecessary collections, while computer vision and machine learning enhance waste segregation by utilizing image recognition to distinguish recyclable from non-recyclable materials on conveyor belts, thereby increasing the speed and accuracy of sorting processes [52]. These intelligent systems continuously learn to identify new materials and patterns of contamination, thereby boosting recycling rates and reducing reliance on landfills. AI also powers smart bins equipped with fill-level sensors and communication modules that alert waste operators when the bins are full, reducing bin overflow and enhancing urban cleanliness. Moreover, AI supports policy development and public engagement by analysing disposal behaviors, informing targeted campaigns, and enabling tools such as chatbots to educate citizens on proper waste management practices. By mimicking human problem-solving and pattern recognition, AI systems continually improve over time, making waste management more innovative, efficient, and cost-effective for cities and organizations [112].

Machine learning enables systems to learn from past data and make accurate predictions for the future, making it especially valuable in solid waste management. For example, machine learning can predict neighbourhood waste generation by analysing historical data, weather conditions, and public events. Algorithms such as Random Forests (RF), Linear Regression (LR), Support Vector Machines (SVM), K-Nearest Neighbours (KNN), Decision Trees (DT), Artificial Neural Networks (ANN), Reinforcement Learning (RL), and Genetic Algorithms (GA) have shown considerable promise in this domain. RF models efficiently handle complex, multidimensional datasets, improving sorting accuracy and reducing contamination. It enhances the accuracy of waste sorting systems, resulting in lower contamination rates in recycling streams [60]. Researchers have applied CNNs to classify images of waste, distinguishing between recyclable and non-recyclable items, and sorting waste bags [87]. RF models accurately predict the status of waste bins, indicating when collections are required. Their ease of implementation and interpretability make them practical tools for enhancing waste management processes. Researchers have applied RF models to forecast waste generation, optimize collection routes, and improve strategies for waste treatment and disposal [12, 25, 60]. KNN excels at classifying waste based on physical attributes [60], while DTs offer interpretability and simplicity for classification and prediction tasks. They are effectively employed in improving waste generation predictions and optimizing waste management planning [60]. ANNs, inspired by the human brain, capture complex, nonlinear patterns and support multi-tasking. ANN models are used to optimize waste generation and waste management planning [12, 60]. RL algorithms dynamically optimize waste collection and resource allocation based on real-time data, resulting in adaptive and sustainable systems [60]. GAs, rooted in evolutionary principles, solve complex optimization problems such as route planning and resource distribution but demand careful model design and are less efficient for simpler tasks. They optimize waste management planning and vehicle routing [12, 60]. Federated Learning facilitates decentralized modeling of waste generation trends across multiple locations while preserving data privacy [25]. Natural language processing combined with SVMs automates responses to common waste management queries [12, 60, 87]. Hybrid machine learning and deep learning models enable the real-time detection, classification, and sorting of waste, thereby optimizing collection and recycling processes [26, 87]. Additionally, computer vision techniques enable the prediction of waste generation patterns, optimize collection routes, and automate waste segregation [24]. These machine learning techniques collectively contribute to more innovative, more efficient, and adaptive waste management solutions.

Deep learning, an advanced subset of machine learning, uses multiple layers of neural networks to process complex data such as images and videos [113]. In smart waste management, deep learning enables automated systems to recognize and classify waste items using image analysis from cameras placed over conveyor belts [114]. These neural networks learn to distinguish materials such as plastic, metal, paper, and food waste, improving their accuracy with increased exposure to data. CNNs, known for their high performance in image recognition, outperform other models, such as Recurrent Neural Networks (RNNs) or transformers, in visual classification tasks, making them ideal for this application. CNNs contribute to operational efficiency by predicting waste accumulation, optimizing collection routes, and minimizing fuel use and emissions [22, 26, 115]. Recent advancements in computer vision have significantly improved the precision and efficiency of waste sorting systems [115]. AI-powered image recognition and machine vision technologies are rapidly gaining traction in this field, using high-resolution cameras, advanced image processing, and deep learning—particularly CNNs—to analyze waste images and accurately determine material composition. These systems, when integrated with conveyor belts, enable real-time, high-speed detection and sorting of waste, thereby enhancing recycling efficiency across various settings [12, 116].

AI-driven waste management systems are revolutionizing waste handling by automating processes, improving efficiency, and reducing costs. These systems enable automated waste sorting through AI-powered robots that utilize computer vision and deep learning to accurately distinguish recyclables from non-recyclables. They also utilize machine learning models to predict equipment failures in waste treatment plants, thereby minimizing downtime and enhancing operational efficiency. Additionally, AI optimizes waste-to-energy processes by enhancing incineration performance, maximizing energy recovery, and lowering emissions. AI plays a transformative role in modern waste management by enabling data-driven decision-making, automation, and predictive analytics, thereby enhancing efficiency and sustainability. AI systems analyze vast amounts of historical and real-time data to optimize waste collection routes, forecast generation patterns, and allocate resources efficiently, significantly reducing fuel consumption, operational costs, and environmental impact [22, 60]. Machine learning, computer vision, and robotics automate waste sorting, enhancing recycling accuracy and throughput while minimizing contamination and manual labour [53]. Smart systems—integrated with IoT sensors, edge computing, and GIS—monitor bin fill levels, detect anomalies, and dynamically schedule collections to avoid inefficiencies such as empty-bin pickups or overflow. AI-driven quality control ensures the production of high-grade recycled materials, while predictive maintenance prolongs the lifespan of vehicles and infrastructure [12]. In smart cities, AI supports sustainable urban planning through real-time dashboards and policy modeling tools, enabling decision-makers to implement efficient and adaptive strategies [23]. Regional applications demonstrate AI's versatility, from advanced robotic systems in developed regions to mobile-based, sensor-equipped solutions in resource-constrained settings, highlighting AI's potential to revolutionize waste management globally [1].

The integration of AI into waste management systems offers substantial potential to advance circular economy goals, minimize environmental footprints, and enhance urban sustainability practices. However, realizing these benefits requires overcoming key challenges, including high initial investment costs, data privacy concerns, and the demand for skilled personnel to operate and maintain AI technologies [57].

Artificial Intelligence is transforming smart waste management by optimizing every stage of the waste lifecycle, from collection and sorting to recycling and disposal. Table 4 provides a brief description of the primary roles AI plays in smart waste management systems.

Table 4. Summary of key roles AI plays in the domain of waste management.

S/No	Roles	Brief Description	References
1	Waste generation	AI plays a crucial role in smart waste management by predicting waste generation and forecasting demand, which supports the	[12, 23]

	prediction and demand forecasting	development of sustainable smart cities. By analysing real-time data from IoT sensors and historical patterns, AI models, such as ANNs and RF algorithms, can accurately forecast the volume and timing of waste across various city zones. This enables dynamic scheduling, efficient resource allocation, and proactive service planning. Predictive analytics allow cities to anticipate fluctuations in waste production resulting from seasonal changes or public events, thereby supporting circular economy initiatives. AI systems prioritize waste collection in densely populated and high-traffic areas to prevent bin overflow and reduce public health risks. They also assist waste management companies in optimizing operations by analysing past collection records, population trends, and event calendars to adjust routes and deploy additional trucks as needed. Additionally, AI enhances safety by working with smart bins that detect hazardous gases, such as methane and ammonia, and send real-time alerts when levels become dangerous. When combined with cloud computing and Blockchain, AI facilitates secure, interoperable data sharing and equips policymakers with actionable insights for long-term urban planning, ultimately promoting efficient, resilient, and environmentally sustainable cities.	
2	Smart bin monitoring and manageme nt	AI-powered smart bins are transforming waste management in sustainable smart cities by enabling real-time, data-driven decisions and improving operational efficiency. Equipped with IoT sensors, these bins constantly monitor fill levels, waste types, and environmental conditions, transmitting data to centralized platforms. Advanced AI algorithms, such as RF and deep learning, analyze this data to predict bin fill times with an accuracy of up to 99.25%. This predictive capability enables cities to optimize collection schedules, prevent overflows, and eliminate unnecessary trips, thereby significantly reducing fuel consumption, travel time, and carbon emissions. Additionally, some systems utilize AI-powered image recognition to distinguish between biodegradable and non-biodegradable waste at the source, thereby enhancing recycling efforts and promoting environmental sustainability.	[25]
3	Optimized waste collection routing	AI-powered route optimization in smart waste management utilizes real-time data from IoT-enabled bins, GIS mapping, traffic conditions, and bin fill levels to dynamically generate efficient garbage collection routes. Advanced algorithms such as Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and RL drive significant reductions in fuel consumption, travel time, operational costs, and environmental impact. Research shows that these systems can improve route efficiency by up to 32%, reduce emissions and fuel use by 29%, and decrease collection trips by 25%, all while preventing bin overflows and ensuring timely waste disposal. Cloud-based platforms and edge computing enhance scalability and responsiveness, while Blockchain technology provides secure and transparent data sharing among stakeholders. These innovations enable cities to	[21, 23, 117]

		adapt to changing waste volumes, optimize resource use, and advance circular economy objectives. Economic assessments reveal long-term savings of millions and substantial reductions in carbon emissions.	
4	Waste sorting and recycling automation	AI-powered computer vision systems now automate the sorting of recyclables from general waste by leveraging advanced image recognition and classification techniques. Using high-definition cameras and sensors, platforms like ConvoWaste scan items on conveyor belts and apply CNNs to identify materials, such as plastics, metals, paper, and organics, with an accuracy of up to 99.95%. Robotic arms or air jets then rapidly separate these materials into designated bins, boosting recycling rates, minimizing contamination, and reducing the need for manual labour to enhance worker safety. Integrated with robotics and IoT sensors, these AI-driven systems operate in municipal waste treatment plants, where they support circular economy goals through real-time analytics and adaptive decision-making.	[8, 23, 60, 75, 118, 119]
5	Waste compositio n analysis	AI leverages sensor data, spectroscopy, and imaging techniques to accurately analyze waste composition, using ANNs and advanced image processing algorithms to classify municipal solid waste, such as organics, plastics, paper, and textiles. By processing data from IoT sensors, meteorological inputs, and real-time imaging, these models achieve high performance, with some reaching correlation coefficients above 0.91 for organic waste prediction and classification accuracies of up to 99.62% through the application of deep learning and optimization methods. AI enables rapid, cost-effective, and scalable waste assessments. It dynamically adapts to seasonal or event-driven changes in waste streams, enhances recycling rates, and supports targeted waste management strategies. When integrated with digital twin and IoT technologies, AI delivers real-time monitoring and predictive insights that optimize waste processing and reduce dependence on landfills.	[75]
6	Environme ntal impact assessment	AI enhances sustainable waste management by simulating and predicting the environmental impacts of different strategies. By analysing key variables such as greenhouse gas emissions, energy consumption, and pollutant output, AI enables policymakers to design data-driven, sustainable frameworks. Real-time analytics, machine learning, and IoT sensors allow AI-powered systems to monitor waste generation, collection, and processing, accurately modeling resource use and pollution levels. These technologies optimize collection routes, boost recycling rates, and support circular economy practices, resulting in reduced fuel consumption, lower emissions, and a lower reliance on landfills. AI-driven decision support tools and visualizations enhance transparency, enabling policymakers to develop targeted strategies that minimize environmental harm. For example, integrating AI and IoT into waste systems has reduced fuel use and emissions by 29% and cut collection trips by 25%. AI also forecasts waste generation trends and assesses the feasibility of various methods, supporting long-term	[8, 23, 75]

		planning and regulatory compliance. By automating environmental monitoring, AI enables cities to adapt to changing conditions, allocate resources efficiently, and achieve measurable progress toward sustainability goals.	
7	Citizen engagemen t and awareness	AI enhances citizen engagement and awareness in smart waste management by promoting transparency, participation, and behavioural change. AI-driven platforms educate the public through real-time feedback and personalized waste disposal instructions, delivered via mobile apps and chatbots, to encourage proper waste segregation and community involvement. Visualization tools and predictive models present waste management processes, air quality data, and environmental impacts in accessible formats, empowering citizens to make informed decisions and support sustainability. Smart waste platforms integrate mobile and web interfaces that enable users to monitor the status of public bins, receive alerts, and access educational resources, fostering responsible disposal and recycling habits. AI-powered systems personalize communication, deliver targeted awareness campaigns, and motivate positive behaviors through gamification and rewards. By combining AI, IoT, and community feedback, these collaborative frameworks build trust, enhance transparency, and promote shared responsibility for urban cleanliness. Research consistently highlights how citizen participation, enabled by digital tools and AI analytics, drives both efficiency and the cultural shift essential for sustainable waste management.	[8]

Robotics in Smart Waste Management

Robotic technologies are transforming urban smart waste management by enabling more sustainable and efficient waste disposal practices. Robotics combines mechanical engineering, electrical engineering, computer science, and AI to design, build, program, and operate robots [28]. These programmable machines perform tasks autonomously or semi-autonomously, often in hazardous, repetitive, or precision-demanding environments. Robotic systems use sensors to perceive their surroundings, actuators to enable movement, control systems to guide decision-making, and algorithms to support learning and adaptation.

Robots increasingly drive efficiency, safety, and sustainability in modern waste management by streamlining processes across the entire waste lifecycle—from collection and sorting to recycling and disposal. In urban settings, smart waste management systems utilize various types of robots to handle the increasing volume and complexity of waste. Autonomous waste collection robots utilize GPS, LiDAR, and computer vision to navigate and retrieve waste from bins, often in conjunction with smart sensors that signal when bins are full, thereby optimizing routes and reducing fuel consumption. Sorting robots in material recovery facilities rely on AI and machine learning to rapidly and accurately separate materials, boosting recycling rates and lowering contamination. Robotic bin monitoring units detect issues such as illegal dumping or overflowing bins, sending alerts to human crews for a faster response. Specialized robots handle hazardous waste, utilizing sealed systems and precision tools to safely dismantle and dispose of dangerous materials. Recycling and dismantling robots extract valuable components from electronics and appliances with AI-guided mechanical arms. Meanwhile, swarm robotics enables fleets of robots to work collectively in tasks such as cleaning, sorting, or landfill management. By combining these robotic technologies with AI platforms, IoT sensors, and data analytics, cities can create smart, responsive waste management ecosystems that lower labour costs, protect the environment, and enhance service delivery [114, 120].

Recent advancements in robotics and AI are transforming waste management by enhancing efficiency, accuracy, and sustainability across urban, construction, and recycling domains. AI-powered autonomous vehicles, such as HawkEyes, utilize computer vision to identify and categorize urban waste, streamlining cleanup operations and reducing reliance on manual labour. In construction, robots sort materials such as concrete, wood, and metals, minimizing contamination and supporting circular economy goals. IoT-integrated smart compaction systems optimize collection routes, lower fuel consumption, and cut greenhouse gas emissions. These technologies boost sorting speed and accuracy while improving worker safety by reducing exposure to hazardous environments. Collaborative robots (cobots) work alongside human operators, increasing productivity and safety. However, challenges persist, including limited access to high-quality training datasets and the complex, heterogeneous nature of waste materials [12, 28, 121].

In urban waste management, robotics automates collection, sorting, recycling, and disposal processes. AI-driven autonomous vehicles equipped with sensors and cameras optimize routes using real-time data from smart bins, improving efficiency and reducing operational costs. Robotic arms handle a diverse range of waste types with minimal human intervention. At the same time, high-speed sorters in recycling facilities utilize computer vision and machine learning to identify materials with high precision, even distinguishing between different plastic polymers. Robots also manage hazardous and bulky waste, safely dismantling e-waste or handling biohazards. Mobile robots and drones monitor landfills and recycling centers for potential risks, such as leaks or illegal dumping. In waste-to-energy plants, AI-integrated robotic systems adjust processing parameters for optimal energy recovery and perform predictive maintenance to reduce downtime. These technologies collectively enhance urban sustainability, lower environmental impact, and support the shift toward a circular economy [60, 122, 123].

Governments can effectively integrate robotics into waste management by developing comprehensive policies that prioritize sustainability, equity, and innovation. They should establish a supportive regulatory framework that incentivizes the adoption of AI-driven waste technologies through measures such as tax breaks and grants for tech companies and startups. By setting clear guidelines for the safe and ethical use of robotics, particularly in waste processing and disposal, they can ensure the responsible implementation of these technologies. Governments can also foster public-private partnerships to secure funding and align technological progress with environmental and social goals. These policies must emphasize accessibility to ensure that low-income community's benefit from robotic waste solutions. Integrating circular economy principles into waste strategies will further enable robotic systems to enhance recycling, reduce waste generation, and recover valuable resources, advancing long-term sustainability [28].

Robotics plays a crucial role in advancing smart waste management systems by delivering innovative solutions that enhance efficiency, improve safety, and promote environmental sustainability. Table 5 provides a brief description of the primary roles Robotics plays in smart waste management systems.

Table 5. Summary of key roles robotics plays in the domain of waste management.

S/No	Roles	Brief Description	References
1	Automated waste collection	Robotic systems enhanced with advanced sensors, AI algorithms, and IoT technologies are revolutionizing waste collection by automating operations, reducing human labour, and minimizing exposure to hazardous materials. Autonomous mobile robots and self-driving garbage trucks utilize real-time data, GPS, and AI-based navigation to optimize routes, avoid obstacles, and adapt to dynamic urban conditions, thereby increasing efficiency, reducing fuel consumption, and lowering emissions and labour costs. Smart bins equipped with fill-level sensors communicate with central platforms to trigger waste collection when necessary, thereby reducing unnecessary trips and lowering operational expenses. These systems operate continuously, perform repetitive tasks, and improve recycling rates by autonomously sorting waste, thereby reducing the need for manual handling in hazardous environments. IoT integration enables predictive maintenance, real-time monitoring, and data-driven planning, thereby improving resource allocation and enhancing system reliability. Pilot programs in several cities have already demonstrated faster collection times, lower costs, and reduced environmental impact, while advancing public satisfaction and circular economy goals.	[8, 28]
2	Intelligent waste sorting and segregation	Robotics, integrated with machine vision, AI, and the IoT, is transforming waste management by enabling the accurate and real-time sorting of recyclables, organic matter, and non-recyclables. Robotic arms equipped with smart cameras and deep learning algorithms, such as YOLO, MobileNetV2 SSD, and CNNs, can precisely identify materials like plastic, paper, glass, and metal, dramatically increasing sorting speed and accuracy. These automated systems reduce contamination, boost recycling rates, and advance circular economy objectives while lowering operational costs and minimizing human exposure to hazardous waste. Studies have demonstrated classification accuracies ranging from 97% to 99% in both laboratory and real-world environments. IoT-enabled	[8, 27, 122]

		smart bins and sensor networks further enhance efficiency by delivering real-time data that supports dynamic sorting adjustments and optimized waste collection.	
3	Real-time waste monitoring and data collection	Robotic sensors embedded in waste bins and collection points monitor waste levels and composition, transmitting real-time data to centralized systems to enable dynamic pickup scheduling and prevent overflow. Drones and mobile robots survey landfills, assess environmental impacts, and detect illegal dumping. Smart bins equipped with ultrasonic, infrared, and moisture sensors autonomously track fill levels and waste types, sending data wirelessly to cloud platforms or central servers for immediate analysis and response. These robotics and IoT-based systems allow municipal authorities to act quickly, ensuring timely waste collection, minimizing overflows, and reducing public health risks. AI and predictive analytics further enhance efficiency by forecasting waste generation, optimizing collection routes, and facilitating dynamic scheduling, which reduces operational costs, fuel consumption, and environmental impact. Studies and simulations demonstrate that real-time, sensor-driven systems significantly outperform traditional methods in efficiency, emissions reduction, and user satisfaction. Integrating Blockchain and edge computing secures data, enhances transparency, and supports scalability. Together, these innovations elevate waste management practices while informing urban planning and sustainability, making real-time monitoring and data-driven decision-making vital for building cleaner, brighter, and more resilient cities.	[8, 25, 76, 104]
4	Hazardous waste handling and safety	Robots play a critical role in hazardous and medical waste management by reducing human exposure to dangerous substances while enhancing safety and operational efficiency. Specialized robotic systems collect, transport, and dispose of toxic, chemical, and biohazardous waste, ensuring regulatory compliance and safer working conditions. AI-powered autonomous robots, equipped with advanced sensors and multi-modal capabilities, perform high-risk tasks such as soil cleanup, oil spill response, hazardous waste sorting, and disaster recovery with greater precision and effectiveness than human workers. These robots navigate complex environments, detect and segregate hazardous materials, and perform operations that would otherwise pose serious risks to human health. Integrated with IoT and real-time monitoring systems, they enable continuous site assessment, early leak detection, and rapid response. In highly specialized fields like nuclear waste management, autonomous and remote-controlled robots	[28, 124]

		handle radioactive materials, offering vital protection for human operators. To unlock the full potential of robotics in this domain, stakeholders must invest in innovation and promote collaboration among governments, technology developers, and communities to ensure the ethical, safe, and sustainable implementation of robotics.	
5	Waste processing and resource recovery	Robots are transforming waste processing by shredding, compacting, disassembling, and converting waste into valuable resources. Integrated with AI and IoT, these systems enhance the composting of organic waste, the recovery of metals from electronic waste, and material separation. In recycling centers, robots equipped with computer vision, such as YOLOv8x, accurately identify and sort materials like glass, metal, plastic, cardboard, and organic waste, reducing contamination and improving the purity of recyclables. They handle hazardous materials safely, enhance worker safety, and improve operational efficiency. Researchers have developed robots that disassemble electronic waste without damaging small components, sort waste using image analysis, and enhance recovery efficiency. Robotic technologies also advance waste-to-energy processes, including plastic pyrolysis, and track carbon emissions. Meanwhile, smart bins and automated source sorting enhance both upstream and downstream processing. Pilot studies and reviews report a 20% reduction in unrecycled waste and a more than 30% increase in processing throughput, highlighting substantial environmental and economic benefits.	[125, 126]
6	Sewage treatment	Robotic advancements are revolutionizing sewage treatment by increasing efficiency, cutting maintenance costs, and boosting overall system performance. Autonomous robots, equipped with advanced sensors, monitor and inspect sewage pipelines in real time, detecting leaks, blockages, and structural issues as they navigate complex networks. They transmit critical data to operators for swift action and carry out routine maintenance tasks such as cleaning sediment and repairing damage. By minimizing human exposure to hazardous environments, these systems enhance safety and reliability. As technology continues to evolve, integrating robotics into sewage management will drive greater efficiency, sustainability, and protection for public health and the environment.	[127]
7	Waste-to-energy	Waste-to-energy robotics enhances urban smart waste management by utilizing sensors and AI algorithms to sort waste, accurately separating recyclables from non-recyclables with efficiency. When integrated into waste-to-energy systems, these robots streamline sorting and disposal processes, increase energy recovery, and reduce environmental impact. Research indicates that these	[127]

	technologies enhance operational efficiency, reduce costs, and decrease greenhouse gas emissions. As advancements in robotics continue to expand their capabilities and applications within waste-to-energy facilities, cities move closer to achieving sustainable and eco-friendly waste management solutions.

Fusion of Blockchain, IoT, AI, and Robotics for Efficient Waste Management in Smart Cities

Smart waste management has advanced significantly through the integration of emerging technologies, including Blockchain, IoT, AI, and robotics. Together, these technologies create a unified, transparent, and highly efficient system that automates waste collection, sorting, recycling, and monitoring. By working in tandem, they enhance operational efficiency, reduce environmental impact, and ensure accountability across the waste management process. This integrated system functions through interconnected technological layers, each playing a distinct role in optimizing waste handling in smart cities.

Sensing and actuation (device) layer

The sensing and actuation (device) layer serve as the physical interface between the smart city waste management ecosystem and the real world, integrating IoT-enabled sensors, robotic actuators, and edge-level microcontrollers to collect, process, and act on environmental data. In the proposed Blockchain–IoT–AI–Robotics framework, it functions as the primary data source and operational executor, connecting on-ground waste detection, sorting, and collection with higher-level intelligence. Smart bins equipped with ultrasonic, gas, chemical, and weight sensors, as well as cameras and computer vision modules, monitor fill levels, detect hazards, and classify waste in real-time. Robotic arms, AMRs with LiDAR and GPS, and automated compaction systems handle waste autonomously, while event-triggered actuators respond instantly to sensor inputs. The layer uses LoRaWAN, NB-IoT, MQTT, Zigbee/BLE, and 5G URLLC to ensure low-power, reliable connectivity across distributed infrastructure. It secures operations through SHA-256 data hashing, blockchain-based device authentication, and smart contracts that autonomously trigger robotic actions when preset conditions are met. Embedded AI models such as TensorFlow Lite and OpenVINO enable on-device classification, while federated learning nodes in bins and robots enhance models locally with blockchain-secured updates. This integration reduces collection costs by optimizing schedules, boosts recycling accuracy through AI-driven sorting, minimizes environmental risks via rapid hazard response, and enhances operational transparency through immutable blockchain-based data records.

Edge/gateway layer

The edge/gateway layer bridges constrained field devices, such as sensors, actuators, and robots, with higher tiers like fog/cloud, blockchain, and analytics, enabling efficient protocol translation, connectivity, data aggregation, preprocessing, local AI inference, security, blockchain integration, robotics interfacing, and resilience. It uses low-power gateways or SBCs (e.g., Raspberry Pi, industrial gateways, Nvidia Jetson/Orin) with secure elements/TPMs or HSMs, multi-interface connectivity (4G/5G, Ethernet, Wi-Fi, LoRa), and a Linux-based software stack (Yocto/Ubuntu), container runtimes (Docker), messaging brokers (MQTT, Mosquitto), IoT protocol adapters, AI runtimes (TensorFlow Lite, ONNX Runtime, PyTorch Mobile, DeepStream), robotics middleware (ROS/ROS2), blockchain clients, and local time-series databases or IPFS clients. Communication spans device-to-gateway links via LoRaWAN, 6LoWPAN, NB-IoT/LTE-M, and application-layer protocols, including MQTT, CoAP, and HTTPS. Gateway-to-cloud links are supported via HTTPS, MQTT over TLS, gRPC, and WebSockets. Additionally, robotics communication utilizes ROS2 with bridges to MQTT/HTTP, keeping latency-sensitive loops local. Blockchain integration employs SHA-256 hashing, ECDSA/ECDH signatures, Merkle trees for batch commitments, light node/SPV proofs for efficient verification, and off-chain storage (IPFS or cloud) with on-chain hashes or CIDs to ensure immutability, authenticity, and low on-chain load.

Connectivity and message bus layer

This layer bridges physical devices, such as bin sensors, cameras, street-level actuators, collection trucks, and service robots, with higher-order services, including AI analytics, route optimization, and blockchain ledger. It ensures reliable, secure, and scalable transmission of telemetry, commands, and event streams from constrained IoT devices and robots to edge or cloud systems, while delivering control messages back to actuators. It normalizes and enriches device data so that blockchain transactions and AI models receive consistent, authenticated inputs. The key functions include device connectivity via low-power wide area networks, cellular, or short-range links; local aggregation, filtering, and preprocessing at edge gateways; pub/sub or event streaming for real-time flows; durable streaming for audits and historical analysis; secure blockchain anchoring with hashing and signatures; and deterministic middleware for real-time robotics communication. Recommended technologies include LoRaWAN for long-range, low-power urban bin sensors; NB-IoT or LTE-M for mobile or higher-reliability telemetry (e.g., on trucks); CoAP for resource-constrained REST-style device communication; MQTT for lightweight telemetry and command/control; ROS2 over DDS for real-time, QoS-controlled robotic networking; Kafka for city-scale, high-throughput event streaming integrated with MQTT; and gRPC, REST, or AMQP for microservice and API-level integration.

Data, AI, and orchestration layer

The data, AI, and orchestration layer acts as the central hub where raw data from IoT devices and robotics is processed, analysed, and intelligently managed to drive efficient, real-time waste management in smart cities. It seamlessly integrates blockchain for secure, immutable data handling, IoT for sensor-based data acquisition, AI for advanced analytics and decision-making, and robotics for automated waste collection and processing. Utilizing LoRaWAN for energy-efficient, long-range connectivity, it collects data from low-power IoT sensors in waste bins and environmental monitors. Meanwhile, protocols like MQTT facilitate lightweight communication with autonomous waste collection robots. Blockchain, secured with SHA-256, ensures the integrity, security, and traceability of transactions, such as sensor reports, collection schedules, and robotic logs. Smart contracts automate pickups when bins reach predetermined thresholds. AI models analyze sensor data to predict waste trends, optimize robot routes, and process images for waste classification, while natural language processing interprets citizen feedback to enhance service quality. Orchestration frameworks coordinate workflows, data pipelines, and control signals across IoT devices, AI modules, blockchain smart contracts, and robotics using RESTful APIs, gRPC, and event-driven architectures, enabling rapid responses to environmental changes and optimizing operations.

Blockchain and provenance layer

The blockchain and provenance layer forms the foundation of a multi-layered system that integrates blockchain, IoT, AI, and robotics to optimize waste management in smart cities. It ensures the integrity, transparency, traceability, and trustworthiness of all transactions, enabling seamless coordination among diverse devices and autonomous agents. By applying cryptographic hashing (SHA-256) and consensus mechanisms such as Practical Byzantine Fault Tolerance (PBFT) or Proof of Authority (PoA), it guarantees the immutability and security of waste management data, from smart-bin fill levels to robotic vehicle routes. Through LoRaWAN communication, IoT-enabled smart bins and sensors transmit secure, low-power, long-range data to edge or cloud nodes, initiating provenance records on the blockchain. The layer maintains a complete audit trail of waste's lifecycle—from generation and collection to transportation, processing, and recycling—eliminating reliance on central authorities by enabling decentralized verification among stakeholders, including municipalities, waste companies, recycling centers, and citizens. Smart contracts automate key operations, such as triggering robotic collection when bins exceed set thresholds, managing payments, and enforcing compliance. This comprehensive, verifiable provenance system supports real-time monitoring, forensic audits, and performance optimization, rapidly detecting and preventing inconsistencies or fraudulent activities.

Robotics and fleet control layer

The robotics and fleet control layer plays a pivotal role in a multi-layered architecture that integrates blockchain, IoT, AI, and robotics to optimize smart city waste management. It manages the deployment, coordination, and real-time control of autonomous waste collection robots, enabling efficient, adaptive, and responsive operations. This layer orchestrates intelligent robots equipped with sensors and actuators to collect, sort, transport, and dispose of waste, while AI-driven fleet management optimizes routes, schedules, and task assignments to reduce fuel consumption, traffic congestion, and costs. It facilitates bidirectional communication between robots, edge devices, and control hubs for status updates, environment mapping, and collaborative tasks. The layer integrates with the IoT layer by using LoRaWAN to relay bin fill levels and location data from distributed sensors; with the blockchain layer by recording task completions, route logs, and maintenance records on a SHA-256–secured ledger for transparency and auditability; and with the AI layer by leveraging predictive analytics via APIs or message brokers to optimize operations. Employing protocols such as MQTT or ROS for real-time coordination, it delivers operational efficiency, lowers emissions, enhances accountability, and scales seamlessly to accommodate expanding urban infrastructure.

API and user interface layer

The API and user interface (UI) layer serves as the primary interaction point between end-users, such as city administrators, waste management operators, and citizens, and the system's underlying technical components. It abstracts the complex functionalities of IoT devices, blockchain networks, AI models, and robotic systems, delivering a seamless, intuitive, and secure platform for monitoring, controlling, and optimizing waste management operations. Through dashboards and mobile/web applications, it visualizes real-time waste data, collection schedules, bin statuses, and environmental metrics, while providing AI-driven insights, such as predictive robot maintenance and optimized collection routing, along with alerts from AI analytics or blockchain-triggered smart contracts. Acting as a unified API gateway, it securely integrates IoT networks, blockchain ledgers, AI inference engines, and robotic controls, enabling authenticated data retrieval, command execution, and transactional operations. It supports blockchain read/write operations with SHA-256 cryptographic verification, queries IoT sensor data via protocols such as LoRaWAN, and provides endpoints to trigger AI-based waste analysis or robotic scheduling. To ensure security, it utilizes HTTPS/TLS for communication, blockchain-based identity or token authentication for access control, and cryptographic hashing for ensuring the integrity of sensitive data. The layer leverages LoRaWAN for low-power, long-range IoT communication, SHA-256 for immutable blockchain transaction integrity, RESTful or gRPC APIs for scalable interactions, and WebSocket or MQTT protocols to stream real-time updates from IoT devices and robotics to the UI.

Figure 7 illustrates a detailed technical framework for integrating Blockchain, IoT, AI, and Robotics for efficient waste management in smart cities. The data flow in a smart city waste management system integrating blockchain, IoT, AI, and robotics begins with IoT sensors deployed across the city in waste bins, collection points, and transportation vehicles. These sensors continuously monitor key parameters, including bin fill levels (via ultrasonic or weight sensors), temperature, odor (to detect hazardous waste or decomposition), and the GPS location and status of waste collection trucks. The IoT devices generate real-time data streams reflecting waste accumulation, environmental conditions, and operational status, which they securely transmit to nearby edge gateways or cloud servers. Each data packet carries a timestamp, device ID, and sensor readings, enabling accurate tracking and management. Edge gateways validate and filter incoming data, removing noise and verifying sensor authenticity to reduce network load. They then format and encrypt the validated data for secure transmission to the blockchain network. Each data record triggers a blockchain transaction containing the IoT device ID and location, sensor readings, timestamp, and cryptographic signatures to ensure integrity and authentication. Blockchain nodes, distributed across the city or managed by trusted municipal authorities and waste management companies, execute consensus algorithms such as Proof of Stake or PBFT. Once validated, transactions are immutably recorded on the blockchain, providing a transparent and tamper-proof audit trail accessible to authorized stakeholders. Smart contracts within the blockchain automatically enforce predefined rules based on incoming data, such as issuing alerts for full bins. The blockchain-validated data feeds into an AI analytics platform, which performs predictive analyses of waste accumulation trends, identifies optimal collection routes to minimize fuel consumption and time, and detects anomalies like sensor faults, illegal dumping, or hazardous waste. AI models continuously learn from new data, refining predictions and optimizing waste management efficiency over time. Based on AI-generated decisions, control commands are sent to autonomous or semi-autonomous robotic systems for waste collection and sorting. Robots receive these commands through secure communication channels, execute the tasks, and generate status reports or new sensor data, such as the type of waste detected or bins emptied. This feedback is encrypted, transmitted to IoT gateways, and logged as new blockchain transactions, completing the data cycle. Authorized stakeholders, including city officials, waste management firms, and residents, access the blockchain through secure portals, enabling real-time monitoring, service verification, and token-based incentives that reward efficient waste disposal and recycling behaviours.

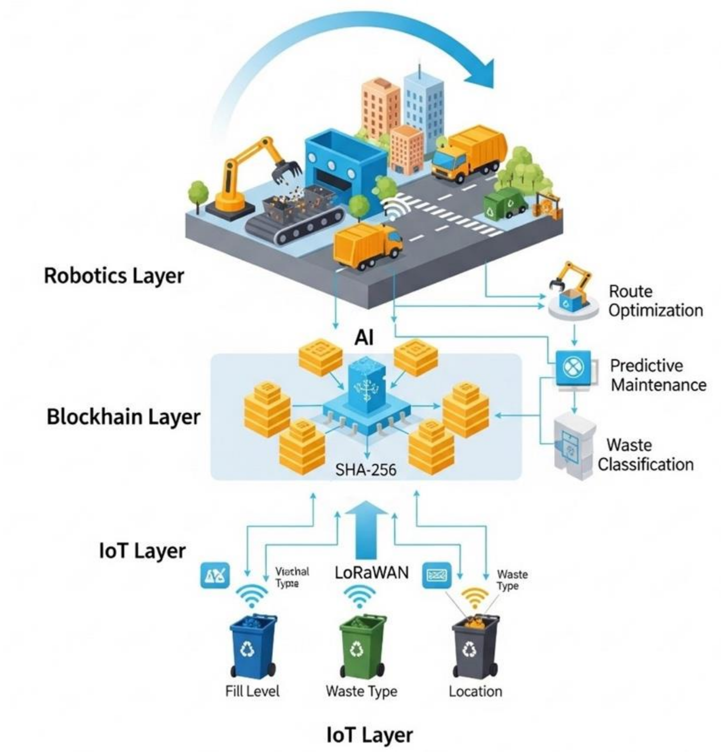

Figure 7. A detailed technical framework for integrating Blockchain, IoT, AI, and Robotics for efficient waste management in smart cities.

The integration of Blockchain, IoT, AI, and robotics has revolutionized urban waste management by enabling real-time monitoring, predictive analytics, automation, and secure data handling. IoT sensors continuously track waste levels and environmental conditions, transmitting data to the cloud where AI algorithms analyze it to predict collection times, identify recyclable materials, and optimize routes. Autonomous vehicles and robotic arms handle waste collection and sorting with high precision, while drones monitor landfills and recycling centers for safety and efficiency. Blockchain technology ensures data integrity, automates billing through smart contracts, and provides transparent, tamper-proof records of waste activities, significantly increasing stakeholder engagement and user trust by up to 95% [25, 26]. Predictive AI models now reach over 99% accuracy, dramatically improving decision-making and operational outcomes. This synergy reduces costs, minimizes landfill use, and enhances recycling efforts, aligning the system with circular economy principles and promoting energy recovery, resource repurposing, and emission reduction [21-26, 56, 128].

By automating processes and scaling efficiently, this integrated approach addresses key challenges, including interoperability, data security, and system scalability. Robotics streamlines sorting, shredding, and compacting tasks, reducing manual labour and boosting throughput [8, 24-26]. AI-powered systems optimize collection routes and predict waste volumes, cutting fuel consumption and operational expenses [8, 26]. Blockchain supports traceability and accountability throughout the waste lifecycle, encouraging citizen participation and policy compliance [24-26]. Scalable architectures, such as LoRaWAN and NB-IoT, facilitate the widespread and cost-effective deployment of IoT devices across urban areas [21, 24]. Collectively, these technologies create a resilient, adaptive, and citizen-centric waste management ecosystem that maximizes material recovery and supports sustainable urban development [129, 130].

Application of Technological fusion for efficient waste management in smart cities

Below are the detailed descriptions of the applications of technological fusion, i.e., Blockchain, IoT, AI, and robotics, for efficient waste management in smart cities.

IoT-enabled smart waste bins

IoT-enabled smart waste bins are transforming urban waste management by integrating cutting-edge technologies, including IoT, AI, Blockchain, and Robotics, to boost efficiency, sustainability, and public engagement. These bins utilize sensors, including ultrasonic, weight, temperature, and gas detectors, to monitor fill levels, detect hazardous conditions, and classify waste in real-time. They transmit data through wireless protocols, such as LoRaWAN, NB-IoT, or Wi-Fi, to centralized platforms [20, 131], where AI algorithms predict waste generation, optimize collection routes, and detect anomalies, including illegal dumping or fire risks. Blockchain technology ensures secure, transparent data sharing, facilitates lifecycle tracking, and enables smart contracts that automate compliance and reward proper waste disposal through token-based systems [20, 21].

Robotics further streamlines operations by automating tasks such as sorting, cleaning, and bin retrieval, thereby reducing manual labour and associated health risks [20]. These systems cut operational costs and carbon emissions by enabling just-in-time, data-driven waste collection, while mobile apps and gamification strategies increase recycling rates and citizen participation [132]. Cities such as Barcelona and Seoul have reported up to 50% improvements in collection efficiency and notable reductions in fuel use and overflow incidents, illustrating the potential of smart bins as a foundational element of sustainable, intelligent urban infrastructure [20, 21, 131].

AI-powered route optimization

AI-powered route optimization is revolutionizing waste management in smart cities by leveraging real-time data from IoT-enabled smart bins, traffic systems, and vehicle statuses to dynamically generate efficient collection routes. These intelligent systems consider bin fill levels, traffic congestion, road closures, weather conditions, and collection priorities to minimize unnecessary trips, fuel use, emissions, and operational costs. Machine learning and predictive analytics enable AI algorithms to adapt routes, ensuring continuous and efficient waste collection [22, 24, 31, [42]. Robotics further strengthens this system by automating bin pickup, waste sorting, and compaction, particularly in narrow or high-risk areas, thereby reducing labor demands and enhancing safety [23, 24, 31]. Meanwhile, Blockchain technology secures transparency, accountability, and data sharing through tamper-proof logs and smart contracts that automate payments based on verified task completion [23, 24]. Studies from cities like Beijing and Lahore demonstrate that integrating these technologies can reduce collection trips by 25–32%, emissions by up to 29%, and bin overflow incidents by 30%. By combining AI, IoT, robotics, and Blockchain, municipalities can develop adaptive, data-driven waste management systems that enhance public hygiene, lower costs, and bolster urban resilience and liveability [22-24, 31].

Blockchain-based waste tracking

Blockchain-based waste tracking is transforming smart waste management by providing secure, transparent, and tamper-proof records throughout the entire waste lifecycle—from generation and collection to recycling and disposal. By integrating Blockchain with IoT, AI, and robotics, smart cities can build a real-time, data-driven ecosystem that improves traceability, ensures regulatory compliance, and boosts operational efficiency [25, 26]. IoT sensors embedded in bins, vehicles, and sorting facilities collect data on waste type, volume, location, and movement, which AI algorithms analyze to optimize scheduling, routing, and processing. A distributed ledger immutably records all events, preventing data tampering and enabling automated processes through smart contracts, such as verifying compliance, initiating payments, and enforcing environmental regulations [25, 26]. Robotic systems enhance precision in sorting and verification, with their outputs securely logged for auditing. This integrated framework enhances stakeholder collaboration, fosters public trust, and utilizes token-based incentives to promote proper waste disposal [25, 26]. By eliminating inefficiencies, ensuring accountability, and advancing circular economy practices, Blockchain-powered systems drive cleaner, more resilient, and sustainable urban development.

Robotic waste sorting

Robotic waste sorting is revolutionizing smart city waste management by integrating robotics, AI, IoT, and Blockchain to improve efficiency, accuracy, and sustainability. AI-powered robotic arms, utilizing computer vision and machine learning models such as CNNs and hybrid CNN-transformers, autonomously identify, classify, and sort waste with up to 99% accuracy [71, 133]. These systems operate continuously, minimize human exposure to hazardous materials, and adapt in real time to diverse waste streams using data from IoT-enabled smart bins and sensors. AI enhances sorting precision through image analysis and predictive analytics, while IoT ensures seamless communication among waste sources, robotic systems, and management platforms [8, 27]. Blockchain strengthens transparency and accountability by securely tracking waste and enabling incentive mechanisms for proper segregation [8]. Real-world implementations, such as ZenRobotics in Finland, AMP Robotics in the USA, and smart bin ecosystems in India and the UAE, demonstrate the global scalability and effectiveness of these technologies. Although initial costs and technical complexity remain challenges, robotic waste sorting significantly boosts recycling rates, reduces landfill use and emissions, and advances circular economy goals, ultimately creating cleaner, safer, and more resilient urban environments [8, 28].

Decentralized recycling incentives via Blockchain tokens

Decentralized recycling incentive schemes that integrate Blockchain, IoT, AI, and robotics are revolutionizing smart waste management by encouraging eco-conscious behavior and advancing urban sustainability. These systems reward citizens and businesses with digital tokens—earned through mobile apps or smart bins—for properly recycling or disposing of waste in an environmentally responsible manner [29]. Blockchain ensures transparent and tamper-proof tracking, automating rewards via smart contracts. This allows users to redeem tokens for utilities, transportation, goods, services, or even participation in local governance [19]. IoT devices, such as sensor-equipped bins and RFID tags, capture real-time data on waste type, quantity, and depositor identity, which is then fed directly into the Blockchain [19, 29]. AI algorithms classify waste using computer vision, analyze user behavior, and optimize collection routes, while robotics enhances efficiency and safety through automated sorting, drones, and autonomous vehicles [19]. Case studies, such as Swachhcoin, Plastic Bank, and Recereum, demonstrate that these schemes have a significant impact, increasing recycling rates, doubling user participation, reducing fraud, and supporting data-driven decision-making. By aligning individual incentives with environmental objectives, these integrated technologies create a circular, participatory, and efficient urban waste ecosystem [19, 29].

AI-driven waste forecasting and demand prediction

AI-driven waste forecasting and demand prediction are transforming smart waste management in smart cities by harnessing real-time data from IoT sensors, advanced machine learning models, and integrated digital platforms. These systems analyze inputs from smart bins, environmental sensors, and historical records to accurately predict waste generation patterns, bin fill levels, and collection demands [22, 23, 30]. By enabling proactive planning, dynamic route optimization, and efficient resource allocation, AI models — such as LSTM, GRU, RF, and hybrid neural networks — achieve over 95% accuracy in forecasting waste accumulation, thereby preventing overflow and streamlining collection schedules [30]. Policymakers utilize these insights to tailor waste management strategies according to population density and usage patterns [22, 23]. Municipalities convert predictions into Demand Prediction Tokens (DPTs), which represent specific waste service needs and can trigger automated robotic actions via Blockchain-based smart contracts. These tokens facilitate just-in-time processing, incentivize communities, and support market-based waste services. AI-guided robotics and drones handle collection, sorting, and monitoring, while Blockchain ensures secure, transparent records, and cloud platforms enable scalable analytics. This integration of AI, IoT, Blockchain, and robotics reduces costs, boosts recycling, advances circular economy goals, enhances urban planning, and strengthens disaster resilience—ultimately turning waste into a predictable, manageable, and economically valuable asset for smart, sustainable cities [22, 23, 30].

IoT-connected wastewater monitoring

IoT-connected wastewater monitoring systems are revolutionizing smart city infrastructure by enabling real-time, automated tracking and control of water quality and treatment processes. Sensors deployed throughout sewer networks and treatment plants continuously measure key parameters, such as pH, temperature, turbidity, flow rate, and pollutant levels, and transmit this data via wireless protocols like LoRaWAN, NB-IoT, and Zigbee [134-136]. Edge or cloud-based platforms then use AI algorithms to analyze the data for predictive maintenance, anomaly detection, and process optimization. Blockchain technology secures the data, ensuring transparency, immutability, and decentralized access, while smart contracts automate regulatory compliance and enforcement. Robotics enhances system efficiency by inspecting pipelines, removing debris, and performing repairs in hazardous environments, thereby reducing manual labour and improving safety. Together, these technologies form an integrated, self-aware, and responsive cyber-physical system that minimizes environmental impact, optimizes resource use, and supports smart governance. Research indicates that IoT-based wastewater systems can achieve recycling rates exceeding 90%, enhance operational efficiency, and generate critical data to combat water scarcity and promote environmental sustainability [134, 136, 137]. Despite challenges such as sensor calibration, energy requirements, and cybersecurity risks, these systems play a crucial role in advancing the UN SDGs—particularly SDG 6 (Clean Water and Sanitation), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action).

Smart E-waste collection and management

Smart e-waste collection and management systems utilize IoT, AI, robotics, and Blockchain to address the growing volume and hazardous nature of e-waste in smart cities.

IoT-enabled bins with real-time sensors detect e-waste type, volume, and fill levels, triggering automated collection schedules and optimizing routes to cut costs and reduce environmental impact. AI models, such as MobileNet and YOLO, accurately classify and sort e-waste, facilitating the recovery of valuable materials, including metals and plastics, for reuse in products like solar batteries [138]. Robotics, guided by computer vision, performs automated sorting and safe disassembly, minimizing human exposure to toxic substances and boosting material recovery [138]. Blockchain ensures transparency and traceability by securely recording disposal, transport, and recycling data on distributed ledgers [139]. It also supports Extended Producer Responsibility (EPR) enforcement and enables smart contracts that incentivize responsible disposal through tokenized rewards. Cloud platforms and mobile applications enhance system intelligence by enabling predictive analytics, stakeholder coordination, and data-driven decision-making. Collectively, these technologies turn e-waste into a valuable resource stream, advancing circular economy goals and fostering environmental sustainability in smart urban environments [138, 139].

Autonomous waste collection vehicles

Autonomous waste collection vehicles are revolutionizing smart city waste management by leveraging robotics, AI, IoT, and Blockchain to deliver efficient, safe, and environmentally sustainable operations. These vehicles utilize AI-driven algorithms, such as deep RL and deep Q-networks, to dynamically optimize collection routes in real-time, drawing on data from IoT-enabled smart bins, traffic conditions, and battery status. This approach reduces travel distances by up to 30%, shortens response times by 28%, and cuts energy consumption by 30% compared to conventional methods [31]. Equipped with advanced driver-assistance systems (ADAS), LiDAR, GPS, cameras, and robotic arms, they autonomously navigate urban landscapes, avoid obstacles, and perform waste segregation to improve recycling rates and reduce manual labor [32]. IoT sensors continuously track bin fill levels, waste composition, and environmental conditions, transmitting data via LPWAN or 5G to centralized platforms for real-time route optimization and predictive maintenance [31, 140]. Blockchain technology secures and transparently logs each waste transaction on distributed ledgers, enabling automated payments, incentive programs, regulatory compliance, and greater stakeholder trust [140]. By eliminating redundant trips, enhancing material recovery, and automating key processes, these vehicles reduce greenhouse gas emissions, lower labour costs, improve urban cleanliness, and advance circular economy objectives—positioning themselves as vital assets in the smart cities of the future [31, 32, 140].

Digital twins for waste system simulation

Digital twins use real-time data from IoT sensors, AI analytics, robotics, and Blockchain to create dynamic virtual replicas of physical waste management systems, enabling cities to monitor operations, predict behaviours, and optimize the entire waste lifecycle—from generation and collection to treatment and disposal. By simulating system performance and testing interventions without disrupting real-world processes, digital twins improve operational efficiency, reduce costs and emissions, and support urban sustainability. Cities leverage these models through interactive dashboards and geospatial tools to anticipate needs, automate responses, and enhance resource allocation. In sorting plants, digital twins automate processes both online and offline, improving resource recovery and minimizing environmental impact. They aid municipal decision-making by modeling trade-offs between cost and service quality, offering performance benchmarks and indicators. Integrated AI and machine learning capabilities allow digital twins to forecast waste generation, optimize collection routes, schedule maintenance, and simulate policy or emergency scenarios [141-143]. Blockchain ensures secure data sharing and automates transactions through smart contracts, while robots respond in real time to digital twin guidance to enhance sorting and collection. By modeling waste flows, infrastructure stress, energy recovery, and disaster responses, digital twins enable stakeholders to visualize, test, and optimize operations, advancing circular economy goals and driving smarter, safer, and more sustainable waste management across smart cities [33, 63, 144].

Blockchain for hazardous waste compliance

Blockchain technology ensures hazardous waste compliance within smart waste management systems in smart cities by creating a decentralized, tamper-proof ledger that tracks dangerous waste from generation through transportation, treatment, and disposal. This approach directly addresses issues such as illegal dumping, data manipulation, and fragmented stakeholder information [7]. Smart contracts automate regulatory checks, documentation, and enforcement, triggering immediate actions upon violations, while secure, permissioned access facilitates transparent yet confidential data sharing among producers, transporters, and regulators [145]. By integrating with IoT devices, the system continuously monitors geolocation, temperature, and container integrity in real time, enhancing safety and enabling swift incident response. Blockchain also ensures full auditability and provenance, streamlining compliance audits and supporting adherence to international environmental standards. These capabilities collectively enhance environmental protection, safeguard public health, optimize regulatory workflows, and improve operational efficiency. Although challenges such as interoperability and adoption remain, pilot projects and emerging frameworks demonstrate Blockchain's transformative potential, especially when combined with AI, IoT, and robotics, to develop intelligent, data-driven infrastructures that promote the circular economy and environmental resilience in smart cities [7, 146].

AI-based illegal dumping detection

AI-powered computer vision algorithms, particularly CNNs and object detection models such as YOLOv5 and YOLOv8, analyze video feeds from surveillance cameras, drones, and smart sensors to detect illegal waste dumping in real-time [34, 79]. These systems detect unauthorized disposal by examining spatial and temporal patterns, differentiating between routine pedestrian movements and suspicious dumping behaviors, and tracking involved individuals or vehicles using multi-object tracking algorithms, such as DeepSORT [147]. Edge computing enhances responsiveness by processing data locally and generating rapid alerts. Researchers train AI models on custom datasets to enhance the recognition of diverse waste types and dumping behaviors, thereby improving scalability and adaptability across urban environments [34, 79]. IoT devices, including smart cameras and acoustic sensors, continuously monitor the environment and activate geo-fencing to trigger alerts upon detecting unauthorized activity. Blockchain technology secures digital evidence with immutable timestamped records, automates penalties through smart contracts, and enables decentralized citizen reporting. Meanwhile, robotics contributes mobility and physical intervention via autonomous patrol units and waste collection robots. Together, these technologies form an innovative, autonomous framework that strengthens enforcement, reduces environmental harm, lowers operational costs, and fosters civic engagement, advancing the vision of clean, data-driven, and sustainable smart cities [34, 79, 147].

IoT and AI for organic waste-to-energy systems

Smart cities increasingly leverage IoT and AI to transform organic waste into renewable energy through efficient, automated, and data-driven systems. IoT-enabled smart bins, sensors, and meters continuously track waste levels, composition, and environmental conditions, feeding real-time data into centralized platforms that optimize collection logistics, process monitoring, and energy conversion [22, 24]. Embedded sensors monitor key parameters, including temperature, pH, humidity, and methane levels, to maintain optimal fermentation conditions and prevent system failures. AI algorithms, including deep learning models like CNNs, accurately classify and segregate organic waste from mixed streams with over 95% accuracy, surpassing traditional methods and improving feedstock purity and biogas yields [148]. These AI-driven systems forecast energy output, monitor performance, and adjust operational parameters to maximize efficiency and sustainability [148]. For example, smart, self-powered waste management systems integrate IoT and CNNs to automate collection, segregation, and biogas generation, powering streetlights and system functions while converting residual organic matter into fertilizer. They dynamically adjust operations, forecast energy usage, monitor equipment health, and enable predictive maintenance and route optimization, thereby significantly reducing human error, costs, and environmental impact. Additionally, AI supports real-time decision-making, emission control, and adaptive energy distribution across local microgrids, while repurposing leftover digestate as fertilizer to promote circular economy principles. Together, IoT and AI enhance urban resilience by converting organic waste into clean energy and valuable byproducts, making waste management smarter, cleaner, and more sustainable [8, 24, 148].

Robotic street cleaning systems

Autonomous robotic street cleaners are revolutionizing urban sanitation by integrating robotics, AI, IoT, and Blockchain technologies to enhance efficiency, sustainability, and liveability in cities. These robots sweep and vacuum litter, dust, and debris from streets and public spaces, especially during low-traffic hours, to minimize disruption [35, 149]. Equipped with LiDAR, GPS, computer vision, adaptive cleaning tools, and real-time obstacle avoidance, they navigate complex urban environments autonomously or remotely. IoT sensors embedded in both the robots and city infrastructure track air quality, dust levels, and equipment health, enabling real-time scheduling and seamless communication between vehicles and infrastructure. AI algorithms optimize cleaning routes, predict demand, diagnose faults, and continually improve performance, thereby reducing resource consumption [35]. Blockchain technology secures cleaning records, automates service contracts, and fosters public engagement through decentralized platforms. Cities like Singapore and Barcelona have piloted these systems, where AI models, such as YOLO, and hardware, like the Nvidia Jetson Nano, enable precise waste detection and collection [149]. Additionally, smart features such as solar power and automated trash cans enhance sustainability. Multi-robot systems, such as MARBLE, coordinate through cooperative planning and energy-efficient algorithms, reducing costs and emissions by up to 30%. This highlights the crucial role these technologies play in creating clean, efficient, and resilient smart cities [35, 149].

Integrated smart waste platforms

Integrated smart waste platforms combine Blockchain, IoT, AI, and Robotics to create comprehensive, data-driven ecosystems that shift urban waste management from reactive to proactive and predictive. These systems gather real-time data through IoT-enabled smart bins, RFID tags, and GPS-tracked collection vehicles, transmitting it via networks such as LoRaWAN or GSM [36, 54]. AI analyzes this data to forecast waste generation patterns, optimize collection routes, detect anomalies, and support decision-making, cutting operational costs and reducing environmental impact [51, 54]. Blockchain ensures data integrity, transparency, and accountability through immutable records, smart contracts, and token-based incentives for citizens. User interfaces and mobile apps keep citizens engaged with real-time updates, alerts, and feedback channels, fostering a sense of community and accountability [36, 37, 54]. Experimental studies demonstrate improved monitoring accuracy, reduced fuel consumption and collection distances, prevention of bin overflow, and increased public satisfaction. Automation features such as smart lids and real-time alerts further reduce manual effort while enhancing urban hygiene. By offering scalable, efficient, and citizen-focused solutions, these platforms play a crucial role in addressing contemporary waste challenges and promoting sustainable urban living [36, 37].

Efficient waste management in smart cities increasingly depends on the seamless integration of Blockchain, IoT, AI, and Robotics. Achieving this integration, however, poses significant interoperability challenges due to the heterogeneous nature of devices, systems, and data sources involved. Standards such as Open Platform Communications Unified Architecture (OPC UA) and one Machine to Machine (oneM2M) play a crucial role in overcoming these challenges by providing frameworks that enable secure, scalable, and real-time data exchange across diverse systems. OPC UA is a platform-independent, service-oriented architecture widely adopted in industrial automation and IoT environments. It facilitates secure and reliable communication between IoT devices, AI-powered analytics, and robotic systems, supporting real-time monitoring and control in waste management operations [24, 87]. Its support for complex data models and standardized communication protocols makes OPC UA particularly suitable for integrating robotics and AI systems in smart cities. Similarly, oneM2M provides a global standard for machine-to-machine and IoT interoperability. By defining a common service layer and standardized data models, oneM2M enables seamless communication among heterogeneous IoT devices and applications. This framework supports the integration of IoT sensors, AI algorithms, and blockchain-based data management, creating a cohesive architecture for smart waste management systems [24, 87].

Combining OPC UA and oneM2M allows smart cities to bridge the gap between industrial automation systems and IoT-enabled waste management solutions. By mapping oneM2M resources to OPC UA information models, data from IoT devices, such as smart bins and environmental sensors, becomes accessible to industrial applications. For example, an OPC UA server can publish data collected from oneM2M-based devices, enabling real-time monitoring, decision-making, and process optimization. This interoperability significantly improves the efficiency and effectiveness of urban waste management operations. Addressing integration challenges requires careful attention to several critical aspects. First, Blockchain enhances data security and trust by ensuring integrity, transparency, and traceability across the waste management lifecycle. Interoperability standards further improve security by enabling the safe sharing of data among IoT devices, AI models, and robotic platforms, thereby mitigating the risks associated with data silos and manipulation [7, 26, 87]. Second, standards like OPC UA and oneM2M support scalable and flexible system architectures, allowing cities to add new devices and technologies without major reconfiguration as their waste management needs evolve [24, 87]. Third, interoperable frameworks facilitate real-time analytics and automation, enabling efficient waste collection, AI-driven classification, and robotic handling for sorting and disposal [24, 26, 87]. Finally, standardized communication protocols such as LoRaWAN and NB-IoT, commonly deployed alongside OPC UA and oneM2M, provide low-cost, energy-efficient, and reliable connectivity for large-scale urban deployments [24].

Table 6 presents key interoperability standards and their roles in integrating smart waste management.

Table 6. Summary of key interoperability standards and their integration roles in smart waste management.

S/No	Standard/Protocol	Integration Role	Key Benefits	References
1	OPC UA	Secure, real-time data exchange between IoT, AI, and robotics	Scalability, reliability, and industrial compatibility	[8, 24]

2	oneM2M	Common service layer for IoT and M2M	Device interoperability, flexible integration	[8, 24]
3	LoRaWAN/NB-IoT	IoT communication protocols	Low power, wide area, cost-effective	[24]
4	Blockchain	Data integrity, transparency	Trust, traceability, secure transactions	[7, 8, 24, 87]

State-of-the-Art Contribution of Technological fusion for efficient waste management in smart cities

Below are the brief descriptions of state-of-the-art contributions of technological fusion for efficient waste management in smart cities.

End-to-end traceability and immutable provenance

The system records sensor events and transaction metadata on a tamper-resistant ledger, typically a permissioned blockchain, to establish an auditable and immutable provenance chain tracking waste from its source to final disposal. This approach reduces fraud and illegal dumping, verifies recycling claims, and streamlines regulatory audits. Its effectiveness can be evaluated based on the completeness of the provenance record, the accuracy in detecting tampering, and the reduction in audit time.

Decentralized, privacy-preserving data sharing

Fusion architectures integrate on-device processing at the edge (IoT) with privacy-preserving technologies, such as selective disclosure, zero-knowledge proofs, and differential privacy, and enforce blockchain-based access control to enable stakeholders to share data selectively without exposing raw personal or business information. This approach strikes a balance between transparency and privacy, ensuring compliance with relevant laws. Researchers can evaluate these systems using privacy leakage metrics, data utility versus privacy trade-offs, and access-control latency.

Automated contracting and service orchestration with smart contracts

Smart contracts streamline service-level agreements, such as collection schedules, payments, and penalties, while enabling conditional workflows like issuing token rewards for verified recycling. By automating these processes, they reduce administrative overhead, accelerate settlements, and enforce rules objectively. Their effectiveness can be assessed through transaction throughput, contract execution latency, and the extent to which they minimize manual dispute resolution.

Incentive mechanisms and tokenized circular-economy models

Tokenization motivates households, businesses, and informal collectors to segregate and return high-value waste streams, such as e-waste and plastics, by offering micro-incentives. Blockchain-backed credits can be exchanged or redeemed, generating market signals that drive higher recycling rates. Researchers can assess the impact by conducting behavioral experiments, tracking changes in recycling participation, and analyzing metrics related to the circulation of tokens.

Federated and distributed AI for privacy and scale

Multiple stakeholders, such as municipalities, private fleets, and manufacturers, can collaboratively train AI models for waste classification, anomaly detection, and routing using federated learning and distributed model aggregation, all without centralizing proprietary sensor data. This approach preserves privacy, enhances model generalization, and lowers bandwidth requirements. Researchers can evaluate its effectiveness by measuring improvements in model accuracy, communication overhead, and resilience to non-IID data distributions.

Real-time operational optimization through multimodal sensing and AI

By integrating high-frequency IoT sensing of fill levels, contamination, odor, and location with AI-driven demand forecasting, dynamic routing, and load balancing, waste collection systems can perform on-demand pickups and adaptively allocate resources. This approach reduces fuel consumption, lowers emissions, and cuts service costs while enhancing responsiveness. Its effectiveness can be measured through key performance indicators such as reductions in route length, decreased collection latency, lower fuel usage, and improvements in overall service levels.

Autonomous robotic sorting and collection with verifiable feedback loops

AI-enabled robotic systems, including stationary sorters and mobile collection robots, autonomously separate recyclables, assess material quality, and log validated transactions on a blockchain. The tamper-proof ledger ensures accountability by recording each robotic decision, supporting quality control and liability tracking. System performance is evaluated by measuring sorting accuracy, processing throughput, operational uptime, and latency in on-chain verification.

Resilient, interoperable edge-to-cloud architecture

A layered architecture, comprising edge IoT for local inference, middleware for secure data aggregation, and blockchain for decentralized consensus, enhances fault tolerance and scalability. By adopting interoperability standards such as common data schemas and APIs, heterogeneous vendors and cities can seamlessly integrate into the ecosystem. The researchers can evaluate the system through fault recovery time, end-to-end latency, and interoperability tests across devices from different vendors.

Automated regulatory compliance and environmental reporting

By integrating immutable transaction records with AI-driven analytics, organizations can automatically generate auditable compliance reports covering emissions, diversion rates, and hazardous waste movement. Smart rules trigger alerts or enforcement workflows whenever thresholds are exceeded or illegal patterns emerge. This approach enhances the accuracy of compliance reporting, reduces the need for manual effort, and shortens enforcement lead times.

Socio-technical governance and citizen engagement platforms

The fusion creates transparent public dashboards, allowing for verifiable claims about municipal performance, while enabling participatory features such as citizen reporting with on-chain evidence and reward redemption. By embedding governance primitives like multi-signature controls and role-based policies, it empowers distributed decision-making among public agencies, private operators, and communities. Stakeholders can evaluate its effectiveness using user adoption metrics, trust surveys, civic participation rates, and governance response times.

Comparative Analysis of Technological fusion for efficient waste management in smart cities with Recent State-of-the-Art Approaches

Blockchain, IoT, AI, and robotics are transforming waste management in smart cities by boosting efficiency, transparency, and sustainability. Recent studies demonstrate how these integrated technologies outperform other advanced solutions, highlighting both their technical innovations and superior operational performance, as summarized in Table 7.

Table 7. Comparison of fusion and hybrid waste management models in smart cities.

Fusion Approach	Key Technologies	Main Benefits	Limitations	References
Full Fusion (Blockchain, IoT, AI, Robotics)	IoT, AI, Blockchain, Robotics	High efficiency, transparency, automation, and circular economy	Cost, interoperability	[24-26]
IoT, Blockchain, and CNNs	IoT, Blockchain, and CNNs	Support circular economy initiatives.	Cost, interoperability, data security	[39]
IoT, Blockchain, big data, and AI	IoT, Blockchain, big data, and AI	Build a smarter waste system.	Cost, interoperability, data security	[40]
IoT and AI	IoT, AI	Real-time monitoring, predictive analytics	Data security, limited transparency	[21, 42, 70]
Blockchain and IoT	Blockchain, IoT	Data integrity, traceability	Limited analytics, less automation	[7]

Design Strategies for Smart Waste Management Systems in Low-Income Communities: Enhancing Equity and Sustainability

Smart waste management systems can effectively address the unique challenges of low-income communities by prioritizing affordability, inclusivity, and accessibility. Recent research identifies and demonstrates several effective design strategies, emphasizing their practical application and the measurable benefits they offer, as briefly described below.

Affordable sensor technologies

Deploying intelligent recycling facilities equipped with affordable IoT sensors enables real-time monitoring of waste levels, optimizes collection schedules, and lowers operational costs. By integrating low-cost microcontrollers with ultrasonic, weight, and metal detection sensors, these systems maintain economic feasibility in resource-constrained areas [150, 151]. Utilizing low-power wide-area network (LPWAN) technologies, such as LoRaWAN, ensures wide coverage with minimal infrastructure and energy use, making them well-suited for rural and low-income urban settings. This approach extends sensor lifespans and reduces maintenance costs. Moreover, modular sensor node designs enable easy scaling and customization to match varying community sizes and needs, thereby further minimizing initial investments and ongoing expenses [151].

Community and environmental benefits

Smart bins with IoT applications reduce waste overflow, improve hygiene, and create cleaner urban environments, directly advancing environmental justice in marginalized areas [150]. Leveraging real-time sensor data, route optimization algorithms minimize fuel consumption, workforce demands, and collection costs, enhancing operational efficiency for municipalities with limited budgets [51]. Furthermore, mobile and web applications increase transparency by enabling residents to track bin status, report issues, and actively participate in waste management, fostering community ownership and trust [151, 54].

Implementation considerations

Recent research underscores the importance of implementing supportive policies and strengthening local capacity to ensure the long-term sustainability and effectiveness of smart waste systems in low-income settings [50, 150]. To enhance their practicality, designers should adapt these systems to local infrastructure constraints, such as intermittent power supply and limited internet connectivity, by integrating solutions like solar power and hybrid communication networks [54].

Figure 8 presents the key features of affordable smart waste systems for low-income communities.

Table 8. Summary of the key features of affordable smart waste systems for low-income communities.

S/No	Feature	Description/Benefit	References
1	Low-cost IoT sensors	Real-time monitoring, affordable deployment	[150, 151]
2	LPWAN (e.g., LoRaWAN)	Wide coverage, low energy, minimal infrastructure	[151]
3	Modular/scalable architecture	Adaptable to community size and needs	[151]
4	Route optimization	Reduces costs, fuel, and workforce	[51]
5	Community engagement tools	Mobile/web apps for transparency and participation	[151]

6	Environmental justice focus	Cleaner, healthier environments for marginalized	[150]

The socio-economic impact of waste management automation

Integrating Blockchain, IoT, AI, and robotics into smart city waste management increases efficiency and promotes sustainability, but it also creates complex socio-economic challenges, particularly by displacing workers and demanding extensive retraining. The socio-economic impacts include the following. Automation in waste management, driven by AI, robotics, and IoT, can increase labor productivity by up to 25%, reduce operational costs, and contribute to GDP growth through more efficient resource utilization [152, 153]. However, automating routine and low-skilled tasks such as collection and sorting could eliminate up to 98% of these jobs, increasing demand for highly skilled technical roles and widening income inequality, particularly in smaller cities and marginalized communities [152, 154]. While some workers benefit from reduced stress, many face increased job insecurity, lower job satisfaction, and health challenges, with the gains from automation often concentrated among those with better digital access, thereby deepening the digital divide and the algorithmic gap [152].

To ensure automation drives inclusive growth rather than exacerbating socio-economic inequalities, governments, industry, and educational institutions must implement comprehensive workforce transition strategies. These include targeted retraining programs and modular upskilling in digital literacy, AI, robotics maintenance, IoT device installation, blockchain node management, and data analytics, tailored to workers moving from manual to technology-enabled roles [154, 155]. Lifelong learning initiatives should be accessible, affordable, and designed to support vulnerable populations [154, 155]. Meanwhile, apprenticeship and on-the-job training programs enable displaced workers to gain hands-on experience alongside engineers and technicians. Public–private partnerships and training consortia can align curricula with evolving labor market demands, creating industry-recognized certification frameworks [154]. Incentivized learning pathways, such as stipends, micro-credential scholarships, and wage subsidies, further encourage workforce engagement, while community tech hubs provide simulation-based environments for mastering AI-powered analytics, robotic control systems, and blockchain-enabled waste tracking. Complementary measures, including social safety nets, robot taxes, and entrepreneurship support in digital and green sectors, can help mitigate the negative effects of automation and foster equitable economic development [154]. By integrating social impact assessments into technology deployment plans and aligning retraining with smart-city sustainability goals, policymakers can anticipate job market shifts, optimize resource allocation, and ensure that the long-term economic benefits, such as reduced municipal waste management costs, higher recycling revenues, and the creation of specialized tech-driven employment, outweigh initial disruptions [154]. Automation in smart waste management can deliver significant economic and environmental benefits, but it may also exacerbate social inequalities. To ensure a just transition for workers in technology-driven urban environments, policymakers, industry leaders, and community stakeholders must actively implement inclusive policies, provide proactive retraining programs, and foster cross-sector collaboration.

Cost-benefit analysis of implementing smart waste management systems

Integrating Blockchain, IoT, AI, and Robotics into smart waste management systems requires significant initial investment, but it delivers substantial long-term savings and operational advantages. Recent studies have quantified and described these trade-offs, highlighting both the economic and functional benefits of such advanced implementations.

Initial investment costs encompass several key areas. First, hardware and infrastructure require the purchase of smart bins equipped with ultrasonic and weight sensors, establishing IoT connectivity through LoRaWAN and cellular networks, deploying robotics for sorting and collection, and setting up cloud or edge computing platforms [42, 51, 156]. Second, software and integration involve developing and implementing AI algorithms for route optimization, waste classification, and predictive analytics, alongside deploying blockchain platforms to secure data and enable smart contracts [21, 51, 156]. Finally, deployment and training encompass the installation of the system, staff training, and integration of the solution with municipal operations [51, 156].

IoT-enabled and AI-driven waste management systems deliver substantial long-term savings and benefits. By optimizing collection routes, these systems reduce the number of trips, cutting fuel use, time, and vehicle maintenance costs by 29–36% [4, 42]. Automation and real-time monitoring lower manual labor and overtime expenses [21, 42, 51], while AI analytics enhance bin placement and collection schedules, minimizing overflow and missed pickups [4, 51, 156]. These technologies also reduce emissions, boost recycling rates, and advance sustainability objectives [4, 42], all while leveraging digital twins and predictive models to maintain or improve service quality at lower costs [4, 156].

Figure 9 presents the comparison of costs and benefits between conventional and smart waste systems.

Table 9. Comparison of costs and benefits between conventional and smart waste systems.

Aspect	Conventional System	Smart Waste System (IoT/AI/Blockchain/Robotics)	References
Initial Investment	Low	High	[42, 51, 156]
Operational Costs	High	13–36% lower	[4, 42]
Fuel Consumption	High	29% lower	[42]
Maintenance Costs	High	18% lower	[42]
Service Quality	Variable	Maintained or improved	[4, 156]
Environmental Impact	Higher emissions	Lower emissions, better recycling	[4, 42]

Key findings indicate that, although initial costs are higher, systems can recover investments within a few years through long-term operational savings and environmental benefits, particularly in urban areas with high waste volumes [4, 42, 51, 156]. Expanding the system and applying data-driven optimization further amplifies these savings [42, 156]. Moreover, substantial cost reductions can be achieved without compromising service quality by leveraging digital twins and AI for informed decision-making [4, 156].

Strategies for scaling smart waste management solutions in developing countries

To scale integrated Blockchain–IoT–AI–Robotics waste management systems in developing countries, stakeholders must develop context-sensitive strategies that tackle financial limitations, bridge infrastructure gaps, and enhance socio-technical adaptability. Below are some of the approaches that can improve scalability and long-term sustainability:

Adoption of low-cost, locally manufacturable IoT sensors

IoT sensors enable real-time waste monitoring, optimize collection routes, and support predictive analytics. In resource-limited settings, designing cost-effective sensors is essential. Leveraging platforms like Arduino or ESP32 allows local assembly and repair while significantly reducing costs. Incorporating solar power or ultra-low-power designs lowers operational expenses and facilitates deployment in off-grid areas. Additionally, implementing store-and-forward communication protocols ensures continuous data collection even in regions with intermittent network coverage.

Modular and lightweight blockchain frameworks

Deploying blockchain in developing countries often encounters obstacles, such as limited computing power and high energy costs. To address these challenges, modular blockchain architectures provide a scalable solution. By implementing permissioned or hybrid blockchains, developers can reduce consensus overhead by using energy-efficient protocols, such as PoA or PBFT, instead of the energy-intensive Proof-of-Work. A modular, plug-and-play design enables the incremental integration of features, such as privacy modules or smart contracts, tailored to local needs and budget constraints. Additionally, integrating edge computing with blockchain enables data to be processed and verified locally before being committed to the blockchain, thereby minimizing bandwidth usage and transaction costs.

Phased implementation and pilot programs

A phased approach can enhance deployment effectiveness by first launching pilot projects in high-density urban areas to test system interoperability and refine the integration of AI, IoT, and blockchain. Leveraging AI analytics from these initial deployments, the system can then scale strategically, targeting regions with the highest risks of waste mismanagement.

Public–private–community partnerships

Engaging local governments, waste management companies, and community-based organizations fosters shared ownership of waste management initiatives. Local entrepreneurs can operate waste collection nodes using IoT devices and robotics through micro-franchising models, while blockchain-based tokenized incentives motivate citizens to participate in waste segregation and reporting by offering redeemable rewards for utilities or local services.

AI-driven resource optimization

In developing countries, efficient resource allocation is critical. AI can actively forecast equipment failures in IoT and robotic systems, enabling predictive maintenance that reduces downtime and repair costs. Similarly, by integrating AI-driven predictive analytics with IoT sensor data, waste collection routes can be dynamically optimized, minimizing fuel consumption and preventing collection delays.

Policy and standards alignment

Long-term scalability relies on supportive regulatory frameworks that establish interoperability standards for IoT devices and blockchain protocols, preventing vendor lock-in, while incentivizing circular economy practices through tax benefits or subsidies for technology-enabled waste management solutions. Scaling Blockchain–IoT–AI–Robotics waste management systems in developing countries requires deploying low-cost, modular, and locally adaptable technologies, engaging communities, and integrating policies in phased approaches. By combining affordability with technological robustness, these systems can transform waste management from a municipal challenge into an economically and environmentally sustainable service in smart cities.

User engagement strategies to boost public participation in smart waste management

In smart waste management systems that integrate blockchain, IoT, AI, and robotics, users play a crucial role in driving operational success and long-term sustainability. Engaging the public ensures accurate data collection and encourages responsible waste disposal behaviours. System designers can promote active participation by implementing structured training programs and offering gamification-based incentives that motivate consistent and responsible user involvement.

Training and capacity-building programs

Training initiatives should engage citizens, waste collection workers, and community leaders to boost awareness, technical skills, and participation. Implement digital literacy campaigns through workshops and online tutorials that demonstrate the use of mobile applications connected to IoT-enabled waste bins, blockchain tracking systems, and AI-based reporting tools. Provide hands-on waste segregation training in schools, community centers, and marketplaces, showing how sensor-equipped bins detect and reward proper sorting. Equip waste management staff with practical instruction on operating robotic collection systems, performing IoT diagnostics, and validating blockchain transactions to ensure efficient system management. Finally, employ a cascade training model by preparing community champions to share knowledge locally, lowering costs while maintaining cultural relevance.

Gamification techniques for behavioural change

Gamification enhances user engagement in blockchain-enabled waste management by leveraging psychological motivators, including competition, achievement, and rewards, thereby increasing the effectiveness of waste management solutions. Citizens earn blockchain-based tokens for proper waste segregation, timely disposal, and participation in community clean-up activities, which they can redeem for utility bill discounts or public transport credits. Community dashboards showcase top-performing households or neighborhoods, fostering healthy competition. Meanwhile, mobile apps connected to IoT devices track individual contributions in real-time and award badges for milestones, such as "Plastic-Free Hero" or "Waste Sorting Champion." AI algorithms analyze participation patterns to deliver personalized challenges, such as reducing organic waste by 20% in a month. Regular community contests, such as the "Cleanest Street" awards, incentivize collective action and sustained engagement.

Integration of engagement strategies with core technologies

The integration of Blockchain, IoT, AI, and Robotics transforms daily waste management by embedding interactive engagement mechanisms. IoT sensors instantly detect and provide feedback, enabling smart bins to display confirmation messages or emit sound cues when waste is correctly sorted. Blockchain ensures transparency through publicly accessible dashboards that record rewards and performance scores immutably, fostering user trust. AI-driven models analyze behavioral data to dynamically adjust gamification challenges and incentives, while socially interactive robots engage users by educating and entertaining them during waste collection tasks, reinforcing consistent participation.

Socio-cultural adaptation

In developing countries, effective engagement strategies integrate local languages, cultural norms, and community structures. Programs utilize storytelling and visual infographics to clarify complex technical concepts, collaborate with schools and youth groups to integrate waste management awareness into extracurricular activities, and ensure gender-inclusive participation by addressing disparities in access to technology. By combining structured training with culturally sensitive gamification, smart waste management systems not only optimize technological efficiency but also cultivate informed, motivated citizens, laying the foundation for long-term environmental sustainability in smart cities.

REAL-WORLD SCENARIOS AND PRACTICAL IMPLEMENTATIONS OF FUSION OF BLOCKCHAIN, IoT, AI, AND ROBOTICS FOR EFFICIENT WASTE MANAGEMENT IN SMART CITIES

Case studies of practical applications and successful implementations of Blockchain, IoT, AI, and Robotics technologies in waste management

Blockchain, IoT, AI, and Robotics are revolutionizing traditional waste management by creating systems that are more intelligent, efficient, and sustainable. These technologies work together to enable real-time monitoring, predictive analytics, secure data sharing, and automation, effectively addressing long-standing issues such as inefficient collection, environmental degradation, and low resource recovery. This section examines the practical applications and successful implementations of these technologies in waste management.

Smart waste management system for Makkah City using AI and IoT

Qurashi et al. [157] present TUHR, a Smart Waste Management System designed specifically for the unique demands of the pilgrimage season. Leveraging the IoT and AI, TUHR monitors waste levels using ultrasonic sensors embedded in containers at performance sites. When a bin reaches capacity, the sensor signals a microcontroller, which then notifies the appropriate authorities. The system also includes gas detectors to identify harmful substances, enabling timely intervention. By scheduling waste collection in real-time and preventing bin overflows an issue common at large-scale events TUHR significantly reduces inefficiencies typical of traditional waste management systems. AI and machine learning models continuously refine decision-making based on accumulated data, enhancing performance over time. This dynamic and proactive approach not only improves site cleanliness and reduces environmental and health risks but also cuts gasoline use and optimizes resource allocation. TUHR aligns with smart city principles and supports Saudi Arabia's Vision 2030 by promoting innovation, sustainability, and public health.

Smart waste management in Seoul, South Korea

Seoul is pioneering smart waste management by integrating IoT, AI, and Blockchain technologies to enhance waste collection and recycling. Smart bins equipped with IoT sensors monitor fill levels and send alerts only when they require emptying, reducing fuel use, saving time, and minimizing pollution. AI analyzes this data to optimize collection routes, improving efficiency and lowering operational costs. Meanwhile, Blockchain maintains a secure, transparent record of all waste-related activities, enabling residents and city officials to track waste from collection to disposal. This transparency builds trust, prevents fraud, and promotes accountability. By leveraging these technologies, Seoul manages waste more efficiently and sustainably, setting a powerful example for other cities [158].

Smart waste management in the city of Shenzhen, China

Shenzhen leverages advanced technologies, including robotics, AI, Blockchain, and IoT, to enhance its waste management system and increase recycling efficiency. AI-powered robots rapidly and accurately sort materials, including plastic, glass, and metal, streamlining the recycling process. Blockchain technology ensures the secure and transparent tracking of waste activities from collection to recycling. At the same time, smart contracts automate payments to recycling companies upon achieving their targets, making the system more efficient and equitable. IoT sensors installed in public bins monitor fill levels in real-time, optimizing collection routes, reducing fuel consumption, and lowering emissions. Through this integrated approach, Shenzhen is advancing toward its goal of becoming a "Zero Waste" city by 2030, thereby building a smarter, cleaner, and more sustainable urban environment [159].

The smart waste collection initiative in Dubai, United Arab Emirates

Dubai leverages advanced technologies, including AI, IoT, Blockchain, and robotics, to enhance the efficiency and sustainability of its waste management system. Autonomous robots equipped with AI sensors patrol public spaces to detect and collect litter, ensuring cleaner streets with minimal human intervention. IoT-enabled trash bins monitor waste levels and notify collection teams when full, enabling optimized routes that reduce fuel consumption and emissions. The city also employs Blockchain to securely track waste from collection to recycling, ensuring transparency and preventing fraud. Smart contracts automate payments for completed collection tasks, streamlining operations. These integrated technologies align with Dubai's commitment to minimizing environmental impact and building a more sustainable urban waste infrastructure [160].

Smart waste management in the Netherlands

The Netherlands utilizes advanced technologies, including AI, IoT, Blockchain, and robotics, to enhance waste management and support its environmental goals. In many Dutch cities, AI-powered robots accurately identify and sort materials, such as paper, plastic, and metal, at recycling centres, thereby accelerating the process and reducing errors. Blockchain technology increases transparency by tracking waste from collection through recycling, while some communities incentivize residents to recycle using Blockchain-based rewards. Additionally, smart bins equipped with IoT sensors monitor waste levels and transmit real-time data to waste collectors, preventing unnecessary pickups and reducing fuel consumption and emissions. Together, these technologies are driving higher recycling rates and advancing the Netherlands toward a circular economy focused on resource reuse [161].

Plastic Bank — Brazil & other emerging-market sites

Plastic Bank operates collection centers and digital exchanges that convert collected plastic into tokens or monetary value for collectors. Using a permissioned/hybrid blockchain, it records every transaction—from collection to token issuance, transfer, and sale—ensuring tamper-evident provenance without relying on energy-intensive proof-of-work. Collectors log plastic weight or volume via mobile apps or point-of-collection terminals, with digital identities linked to on-chain records. In specific locations, IoT devices, such as digital scales, QR codes, and sensors, reduce manual entry errors. Off-chain AI and analytics forecast supply, match buyers, and measure social impact.

Operating across countries including Brazil, Egypt, Indonesia, the Philippines, and Cameroon, Plastic Bank has distributed millions of kilograms of plastic and provided tangible payments to thousands of collectors. By formalizing informal collection work, the initiative promotes social inclusion; however, token economics and local adoption barriers, such as mobile access and literacy, require further auditing. The blockchain enhances transparency but complements, rather than replaces, strong local operations and digitized front-line tools.

Kigali, Rwanda — Smart Waste Pilot

The Rwandan government, through MINICT and the City of Kigali, in collaboration with partners including RISA, Smart Africa, and donors, launched a Smart Waste Management pilot as part of its CleanKigali smart-city initiative. The pilot deployed solar-powered ultrasound and weight sensors in public bins for organic, inorganic, and e-waste, transmitting fill-level data via cellular or LPWAN networks to a central platform. This data feeds AI-driven or heuristic routing optimizers to schedule timely collections, reduce unnecessary truck mileage, and predict overflow hotspots. While blockchain has not been central to the pilot, it could be integrated to track material provenance for recycling. Early phases in neighbourhoods like "Mpazi" and "Busanza" demonstrated improved monitoring, reduced overflows, and more timely pickups, though precise quantitative metrics are still being consolidated. The rapid deployment benefited from low-cost, locally fabricated sensorized bins and donor support; however, challenges remain in terms of connectivity reliability, sensor maintenance, vandalism, integrating informal collection chains, and financing a city-wide scale-up. Researchers are advised to include lifecycle maintenance data and socio-technical acceptance studies in future evaluations.

Nairobi, Kenya — Tech-Bins / T-Bin & smart-bin pilots

Kenyan innovators and pilot projects, including the "T-Bin," university-industry collaborations, and IBM–municipal initiatives, have trialed solar-powered smart bins equipped with fill-level sensors, incentives such as Wi-Fi access and educational content, and public awareness features. These prototypes focus on source separation and aim to enhance recycling rates in high-traffic areas. The bins utilize IoT sensors—specifically, ultrasound and weight sensors—powered by solar energy and connected via GSM or LoRa to report fill levels. Dashboards aggregate sensor data to optimize collection schedules, while some pilots leverage analytics to identify hotspots and guide public campaigns. Although blockchain integration has not been widely reported in Nairobi, projects that reward citizens for recycling could combine tokenized digital credits with sensor-verified deposits. Media reports and NGO summaries indicate increased engagement at pilot sites and potential reductions in dumping near malls and markets. The systems primarily deliver operational benefits, such as improved scheduling, and social benefits, including education and small incentives. Pilots in visible locations provide valuable insights into human–technology interactions; however, long-term success depends on consistent maintenance, effective municipal procurement pathways, and context-appropriate incentive designs. Linking these bins to blockchain-based reward systems, as exemplified by Plastic Bank, holds strong potential if local social and technical readiness aligns.

Bogotá, Colombia — Informal-sector integration and digitalization

Bogotá has transformed its solid waste management through strategic projects and international partnerships, focusing on integrating thousands of informal recyclers into formalized, digitalized systems that enhance circularity. The city collaborates with partners, including Scandinavian agencies, to explore source separation, digital tracking, and financing models for recycling and waste-to-resource initiatives. It leverages mobile and web platforms to register informal collectors, track deliveries, and streamline payments. Sensorized containers and AI analytics monitor waste flows, prioritize collection routes, and optimize waste management. Meanwhile, blockchain is discussed in regional contexts to ensure traceable recycling, although its municipal adoption remains limited compared to projects like Brazil's Plastic Bank. Bogotá's progress emphasizes institutional and policy reforms mapping informal actors, redesigning service contracts, and piloting source separation while digital tools support coordination rather than driving large-scale automation. Successful integration of informal workers relies as much on social and regulatory design as on technology, demonstrating that digitalization can enhance inclusion, traceability, and financial transparency when aligned with policy, funding, and co-designed interventions.

In many African and Latin American pilot projects, stakeholders achieve immediate gains by combining IoT and AI—utilizing sensors, routing, and analytics—and by leveraging blockchain to ensure transparent and auditable social payments, such as collector incentives. While sorting robots and autonomous collection systems are commercially available and have been piloted in larger recycling facilities worldwide, their deployment across municipalities in Africa and Latin America remains limited, mostly confined to private facilities or discussed in recent research and market forecasts. Over the next three to seven years, robotics is expected to scale rapidly as sorting robots become more affordable and local operators adopt them.

Comparative analysis of smart waste management systems in different urban settings

IoT- and AI-powered smart waste management systems perform differently across urban contexts, as population density, infrastructure availability, and local waste generation patterns directly shape their design and effectiveness.

Population density

In high-density urban areas, IoT-enabled, sensor-based waste collection systems outperform conventional periodic collection by reducing travel distances, minimizing truck usage, and lowering operational costs. In Al Rayyan, Qatar, where residents generate an average of 1.3 kg of waste per person per day, sensor-driven systems have achieved greater cost efficiency, enhanced environmental preservation, and higher public satisfaction compared to traditional methods [162]. Densely populated cities benefit the most from real-time monitoring and predictive routing because of higher waste accumulation rates and the need for frequent collection.

Infrastructure availability

The effectiveness of smart waste collection systems depends heavily on the quality and availability of supporting infrastructure. Strong communication networks such as Wi-Fi, cellular, and LoRaWAN, along with advanced sensor technologies like ultrasonic and weight sensors, enable cities to implement real-time bin monitoring and dynamic routing. In contrast, cities with limited infrastructure must adapt by deploying simpler, modular solutions [162].

Economic and environmental impact

Sensor-based systems consistently improve operational efficiency by reducing employee workload and fuel consumption, resulting in significant economic savings and environmental benefits. These gains are particularly evident in urban environments with high waste generation rates and established infrastructure [162]. By streamlining collection processes, cities can allocate fewer resources to waste transportation while achieving cleaner streets and lower greenhouse gas emissions.

Public satisfaction and service quality

Real-time monitoring and optimized collection schedules enhance public satisfaction by preventing bin overflow and maintaining cleaner urban spaces. This improvement in service quality is especially critical in densely populated areas where limited public space makes waste accumulation more visible and disruptive [162]. By ensuring timely waste removal, cities can foster healthier environments and greater community trust in public services.

Figure 10 presents the comparison of smart waste system performance in different urban settings.

Table 10. Comparison of smart waste management system performance in different urban settings.

Urban Context	Key Features/Challenges	Smart System Benefits	References
High-density, well-infrastructured	High waste volume, advanced networks	Cost savings, fewer trucks, and high satisfaction	[162]
Low-density, limited infrastructure	Lower waste volume, basic networks	May require modular/adapted systems, with less dramatic savings	[162, 163]
Rapidly urbanizing cities	Infrastructure gaps, rising waste	Need for scalable, flexible solutions	[163]

Detailed metrics for case studies, including costs, timelines, and quantifiable outcomes

Recent case studies quantify the costs, timelines, and outcomes of smart waste management systems that integrate digital technologies in urban environments.

Johannesburg, South Africa (African Waste Reclaimers Organisation, BanQu Blockchain Project)

In 2022, municipal and organizational funding supported the adoption of digital technologies, including the BanQu blockchain platform, which enabled real-time monitoring and transparent transactions, thereby improving efficiency and environmental outcomes. During this period, the initiative diverted 9.21% of the city's total waste from landfills and achieved a Zero Waste Index of 0.34, reclaiming 33.82% of resources. It also integrated informal waste pickers into formal systems, enhancing material substitution and conservation [164].

East Mansoura, Egypt (Smart Solid Waste Management Transformation)

The action plan calls for investing in IoT sensors and digital infrastructure, with performance measured over several years through a phased implementation approach. It utilizes International Telecommunication Union (ITU) standard key performance indicators (KPIs) to benchmark improvements in collection efficiency. It employs a data-driven strategy to enhance waste collection and treatment rates, although specific percentage targets are not specified. Aligned with the SDGs, the plan aims to achieve measurable gains in waste management sustainability [165].

Indonesia (PT. XYZ Smart Waste Management Maturity Assessment)

In 2025, an assessment of smart waste management revealed an average maturity level of 3 (Integrated) out of 5 (Smart) on the maturity scale. Investors had already committed funds at the early stage, but they did not disclose the exact amounts. The evaluation highlighted the need for additional investment in governance, technology, and social engagement to enhance operational efficiency and achieve higher maturity levels [166].

Food Supply Chain, Smart City (IoT & AI Integration).

The project will invest in IoT sensors, machine learning, and data analytics platforms, implementing a two-year data collection and analysis period. By improving inventory control and logistics, food waste can be significantly reduced, resulting in lower waste collection and transportation costs through optimized routing and supply chain coordination. These efficiencies will also cut emissions and resource consumption, contributing to circular economy goals [167].

Figure 11 presents the summary of costs, timelines, and outcomes in smart waste management case studies.

Table 11. Summary of costs, timelines, and outcomes in smart waste management case studies.

Location/Project	Costs/Investment	Timeline	Quantifiable Outcomes	References
Johannesburg, South Africa	Municipal/NGO funding	2022	9.21% waste diverted, 33.82% resources reclaimed	[164]
East Mansoura, Egypt	IoT/digital infra.	Multi-year	KPI-based efficiency, SDG alignment	[165]

Indonesia (PT. XYZ)	Early-stage investment	2025	Maturity level 3/5, operational efficiency gains	[166]
Food Supply Chain, Smart City	IoT/AI platform	2 years	Waste reduction, cost savings, and lower emissions	[167]

CHALLENGES AND LIMITATIONS

Integrating Blockchain, IoT, AI, and Robotics into smart waste management offers promising solutions to improve waste handling in smart cities. However, this multidisciplinary approach faces several critical challenges and limitations that hinder its effective implementation, including the following.

Data privacy and security concerns

The integration of Blockchain, IoT, AI, and robotics into smart waste management systems holds transformative potential for sustainable smart cities, but also brings significant data privacy and security risks. IoT sensors and robotic devices collect sensitive, real-time data, such as waste disposal patterns, user behaviour, and location-specific metrics, that AI algorithms use for system optimization. Without robust safeguards, this data remains vulnerable to unauthorized access, breaches, and privacy violations [26, 168]. While Blockchain enhances data immutability, transparency, and decentralized control, it can also expose private information on public ledgers and complicate compliance with regulations like the GDPR. Performance limitations in Blockchain, AI model sensitivity to data noise, and weak privacy measures during data sharing further compound these challenges [85]. To address these issues, researchers are developing advanced solutions such as federated learning and differential privacy, which retain raw data locally and share only aggregated insights. Smart contracts and decentralized storage platforms, such as Interplanetary File System (IPFS), support secure automation and data management. Despite these innovations, cyber–physical threats persist, with attackers targeting both digital and physical elements of smart waste systems, posing risks like data manipulation, denial-of-service attacks, and unauthorized robotic control [85, 168]. Without adequate protection, IoT devices in AI-driven waste management remain exposed to cybersecurity threats that can disrupt operations [60].

Scalability of Blockchain networks

Public Blockchain systems, particularly Bitcoin and Ethereum, face significant scalability challenges that hinder their application in smart city domains, such as waste management. These networks often suffer from low transaction throughput, high latency, and excessive energy consumption—issues that become more pronounced as the number of IoT devices and the volume of data from sensors, AI analytics, and robotics increase [169, 170]. Their consensus mechanisms slow down processing and drive up costs, making them ill-suited for real-time, data-intensive operations [170]. To overcome these limitations, researchers have developed lightweight consensus algorithms, such as

Delegated PoS (DPoS), and adopted distributed storage solutions, like the IPFS, which enhance efficiency in IoT-rich environments [169]. Experimental studies demonstrate that newer platforms, such as Matic, surpass traditional systems in terms of scalability and performance. However, they still necessitate careful architectural planning to prevent bottlenecks as they scale [25]. Additionally, off-chain scaling, sharding, and layer-2 solutions offer further improvements but introduce trade-offs in complexity, security, and interoperability [170].

Interoperability among diverse systems

Interoperability poses a major challenge to integrating Blockchain, IoT, AI, and robotics in smart waste management systems for smart cities. These technologies often rely on different communication protocols, data formats, and standards, which hinder seamless data exchange and coordinated operation [21, 69, 171]. IoT devices from various manufacturers usually fail to connect natively with AI analytics platforms or Blockchain networks, resulting in data silos and fragmented workflows [21, 171]. Legacy infrastructure introduces additional complications due to its lack of flexibility, which is required for real-time, data-driven processes. Although Blockchain enhances trust and transparency, its decentralized nature creates compatibility issues with real-time IoT data and robotic systems. Proprietary vendor ecosystems, inconsistent data semantics, and the absence of open standards and governance frameworks obstruct full system integration [21]. Additionally, underdeveloped security and trust frameworks expose cross-platform communications to potential risks. These interoperability barriers increase system complexity and implementation costs, limit scalability, and reduce the overall effectiveness of smart waste management solutions.

High computational and energy requirements

Integrating Blockchain, IoT, AI, and Robotics into smart waste management systems holds great promise for creating sustainable and intelligent urban environments. However, the combined use of these technologies significantly increases computational and energy demands, posing serious challenges. Blockchain, particularly when utilizing energy-intensive consensus mechanisms such as PoW, necessitates substantial processing power, rendering real-time, large-scale waste tracking inefficient. IoT networks generate constant data streams from thousands of sensors, placing heavy demands on power and communication infrastructure and increasing maintenance burdens. Deep learning models for analytics and robotic control further raise energy consumption due to their reliance on high-performance computing hardware [25, 75]. Robotic systems amplify these challenges through continuous mobility, actuation, and real-time coordination with AI and IoT components [75]. Integrating these technologies into a cohesive framework intensifies resource demands because of interoperability and scalability issues [75], potentially undermining the very sustainability goals that smart waste management seeks to achieve.

Data quality and sensor reliability

Ensuring high-quality, reliable data poses a significant challenge in integrating Blockchain, IoT, AI, and robotics for efficient waste management in smart cities. IoT sensors in smart bins, collection vehicles, and waste processing facilities often produce noisy, incomplete, or inaccurate data due to calibration drift, hardware degradation, environmental interference, and connectivity issues [21, 25, 42]. Inconsistent maintenance, power outages, and sensor aging further exacerbate these problems, undermining AI-driven tasks such as waste classification, route optimization, and predictive maintenance. Poor data quality undermines the performance of AI algorithms, leading to suboptimal decisions and reduced operational efficiency [12, 26]. It also compromises the integrity of Blockchain records; since Blockchain is immutable, it permanently stores erroneous data, eroding trust in the system [25, 26]. Additionally, integrating data from diverse sensors and platforms introduces challenges related to inconsistent formats and standards, further affecting data quality [21]. Overcoming these obstacles is essential for deploying intelligent, automated waste management systems that depend on accurate, real-time data to optimize collection, recycling, and resource allocation [12, 25, 26].

Cost and economic feasibility

Deploying integrated systems that combine Blockchain, IoT, AI, and robotics in smart waste management requires significant upfront investments in hardware, such as IoT sensors, smart bins, and robotic equipment, as well as in software development and secure Blockchain infrastructure. Municipalities, particularly in developing regions, often struggle with budget constraints that hinder the adoption of these technologies [8, 60]. Ongoing expenses for energy consumption, data processing and storage, cybersecurity, and skilled personnel place additional strain on operational budgets. Many urban and rural areas also lack the digital infrastructure and reliable Internet connectivity needed to support and maintain these systems [21, 60]. The integration of multiple technologies requires specialized expertise and frequent maintenance, which escalates operational costs and complicates large-scale implementation [8, 40, 60]. Blockchain infrastructure incurs additional costs due to its intensive computational and storage requirements, while deploying AI entails substantial investments in software, hardware, and infrastructure, often proving incompatible with existing systems. Small and medium-sized enterprises face additional barriers due to the high cost of AI-powered technologies [60]. The uncertain economic feasibility, unclear return on investment, and difficulty in quantifying indirect benefits, such as environmental improvements and transparency, further challenge adoption. Moreover, the rapid pace of technological change risks early obsolescence, demanding continual upgrades and reinvestment.

Latency and real-time processing

Integrating Blockchain, IoT, AI, and robotics into smart waste management holds great promise for enhancing automation, transparency, and efficiency; however, latency remains a significant technical obstacle. Real-time monitoring and rapid decision-making—critical for tasks like robotic waste collection and dynamic route optimization—often suffer from delays across multiple layers. Blockchain networks introduce latency through consensus mechanisms such as PoW, PoS, or Byzantine Fault Tolerance, which slow data propagation and validation. IoT devices generate large volumes of time-sensitive data, but limited bandwidth, unstable connectivity, and network jitter hinder the timely transmission of this data [25, 172]. AI algorithms, especially those driving robotic navigation or predictive analytics, require fast, low-latency data flows; however, inference and training processes can introduce additional delays [172]. When Blockchain acts as a validation layer, it amplifies these latency issues and reduces system responsiveness [25, 26]. Integrating diverse data from IoT sensors, AI models, robotic systems, and Blockchain ledgers adds computational overhead and synchronization delays [26, 172]. While edge computing, hybrid architectures, and lightweight Blockchain solutions, such as DAGs or off-chain protocols, offer some relief, they remain either underdeveloped or insufficiently scalable for large-scale urban deployment [25, 26, 172]. As a result, latency across these interconnected technologies significantly limits the real-time performance and scalability of smart waste management systems in dynamic urban settings.

Complexity of system integration

Integrating Blockchain, IoT, AI, and Robotics into a unified smart waste management system poses significant technical and operational challenges due to the need to coordinate diverse technologies. Each component operates with distinct architectures, protocols, data formats, and performance demands. IoT relies on lightweight, resource-constrained devices and protocols; AI requires high computational power for analytics and inference; Blockchain introduces latency and consensus overhead; and Robotics demands real-time responsiveness and deterministic control [25, 26]. Achieving seamless interoperability and data flow requires sophisticated middleware, standardized APIs, and robust orchestration mechanisms [25, 26]. The lack of universal standards for data exchange and device communication complicates semantic interoperability among autonomous agents. Real-time constraints hinder robotic responsiveness when data must traverse Blockchain or cloud-based AI systems. Scalability adds further complexity, introducing challenges such as data aggregation, hardware compatibility, system updates, and Blockchain network congestion. Security concerns also intensify the difficulty of integration, as trust boundaries remain ambiguous, smart contracts may contain logic flaws, and IoT devices often lack the computational capacity for robust cryptographic protections. While the integration promises automation, transparency, and sustainability, it demands modular architectures, standardized frameworks, and collaborative governance to address high implementation costs, operational risks, and the dynamic requirements of smart urban environments [171].

Legal, regulatory, and ethical issues

Smart waste management systems that combine Blockchain, IoT, AI, and robotics hold transformative promise for sustainable urban development but face significant legal, regulatory, and ethical hurdles. These systems continuously collect and process vast amounts of data, including geolocation and behavioural information, raising serious concerns about data privacy, protection, and compliance with laws such as the GDPR [173]. While Blockchain enhances data integrity and transparency through immutability, it complicates the enforcement of privacy rights, such as the “right to be forgotten.” The absence of unified regulatory frameworks across jurisdictions hinders interoperability and creates ambiguity around data governance, AI ethics, and environmental compliance [50]. Autonomous AI-driven robots and smart bins introduce complex liability issues in cases of malfunctions, environmental damage, or data breaches. Ethical challenges arise from surveillance risks, algorithmic bias, and the potential exclusion of marginalized communities, notably when AI predicts behaviour or automates service allocation. The legal recognition and enforceability of Blockchain-based smart contracts remain uncertain in many countries. The energy consumption of Blockchain and the e-waste from IoT and robotics also threaten environmental goals. Because public trust is vital for adoption, any ethical lapses, lack of transparency, or misuse of data can quickly undermine confidence in these systems.

Limited standardization

The absence of universally accepted standards across Blockchain protocols, IoT communication, AI model development, and robotic control impedes the integration, interoperability, and scalability of smart waste management systems in smart cities. Diverse communication protocols, including Zigbee, LoRaWAN, NB-IoT, Bluetooth, and Wi-Fi, govern the operation of IoT devices such as smart bins and sensors. In contrast, robotic systems often rely on proprietary interfaces that can clash with IoT and Blockchain infrastructures. Fragmented Blockchain platforms, such as Ethereum, Hyperledger, and IOTA, utilize inconsistent consensus mechanisms, smart contract languages, and privacy features, which complicate their integration with AI and IoT. AI models for route optimization, predictive analytics, and robotic vision often lack standardization in training data, evaluation metrics, and deployment environments, which can lead to opacity and raise concerns about transparency and compliance. Robotic platforms vary significantly in terms of hardware and software, and the lack of standardized APIs and middleware hinders their coordination with AI, IoT data streams, and Blockchain authentication [69]. Moreover, varying regulatory frameworks on data privacy, environmental protection, and urban governance further restrict the development of universally applicable solutions [21-24]. Research silos exacerbate interdisciplinary gaps, hindering innovation and preventing the development of cohesive, interoperable systems. Without standardization, developers face increased costs, extended integration timelines, and limited scalability, resulting in many smart waste management projects remaining isolated and difficult to replicate [21].

Robustness and fault tolerance

Ensuring robustness and fault tolerance in smart waste management systems that integrate Blockchain, IoT, AI, and Robotics poses a significant technical challenge, especially in dynamic and harsh urban environments. These systems must maintain reliable operation despite hardware failures, communication breakdowns, cyberattacks, and environmental disruptions [174-175]. The complex interdependencies among technologies mean that a failure in one layer, such as a damaged IoT sensor, malfunctioning robot, or corrupted AI model, can cascade and disrupt the entire system. IoT devices deployed in landfills or streets frequently suffer physical damage, battery depletion, and network instability, which degrade data accuracy and hinder decision-making [175]. Robots must operate reliably in unpredictable conditions but remain vulnerable to mechanical faults, software glitches, and sensor errors. While Blockchain ensures tamper-proof data integrity, its immutability and computational demands limit real-time correction and adaptability in fault-prone settings. AI models, critical for predictive maintenance and route optimization, risk unreliability from data corruption or concept drift. The lack of unified fault-tolerance standards across heterogeneous components complicates coordinated fault detection and recovery. Although approaches such as redundant sensor networks, distributed data collection, edge computing, and adaptive robotic control mitigate some risks, they often increase energy consumption and system complexity, thereby challenging sustainability objectives [174-175].

Privacy-preserving AI techniques

Smart waste management systems that integrate Blockchain, IoT, AI, and Robotics face critical challenges in ensuring data privacy, as they rely on large-scale, real-time data from various sources, including smart bins, robotic sorters, autonomous vehicles, and citizen apps. AI models trained on sensitive data, such as location, energy consumption, and household waste patterns, are vulnerable to privacy breaches, including membership inference attacks, particularly when using centralized training or unsecured edge inference [12]. Although federated learning offers a decentralized alternative, implementing it in multiagent settings presents challenges such as communication overhead, non-IID data distributions, and vulnerability to gradient leakage and poisoning attacks. While differential privacy offers strong theoretical protection, it often compromises model accuracy and imposes significant computational demands, particularly for multimodal data on resource-constrained edge devices. Blockchain enhances data integrity but can expose metadata on public ledgers. Although advanced methods, such as zero-knowledge proofs and homomorphic encryption, hold promise, they remain resource-intensive and challenging to scale. Privacy-preserving machine learning techniques, including secure SVM and encrypted model training, safeguard data and model parameters during processing. Nevertheless, building robust privacy-preserving AI systems demands balancing data utility with privacy, managing computational overhead, and integrating diverse technologies. The lack of standardized privacy protocols and the continuously evolving privacy regulations further complicate implementation and introduce additional technical uncertainties [12][176].

Embedding privacy-preserving mechanisms into system design is crucial for ensuring compliance with regulations, such as the GDPR, and maintaining public trust. Federated learning supports this goal by training AI models locally on IoT edge devices or robotic sorting units, transmitting only encrypted model updates to a blockchain network or aggregation server [177, 178]. This decentralized approach protects raw data, reduces communication overhead, and safeguards proprietary information, enabling the development of collaborative models — such as route optimization — across multiple waste collection stakeholders without data leakage. Blockchain enhances this process by decentralizing aggregation, ensuring transparency, immutability, and auditability, while edge robotics processes data streams securely in real-time. Privacy is further reinforced through the use of advanced cryptographic techniques [177, 178]. Secure Multi-Party Computation (SMPC) allows stakeholders, including municipal authorities and private contractors, to jointly compute analytics, such as recycling rates and contamination levels, without exposing individual datasets [177, 178]. Homomorphic encryption enables computations on encrypted IoT data, allowing smart contracts to automate tasks such as waste collection payments without revealing the raw data [178, 179]. Zero-Knowledge Proofs (ZKPs) verify regulatory compliance without disclosing sensitive operational details, and masking with chained communication in SMPC adds another layer of data obfuscation. Lightweight cryptographic schemes, such as multi-key EC-ElGamal, strike a balance between security and the limited resources of IoT and robotic devices [83]. Together, these methods form a multi-layered privacy-preserving architecture where IoT sensors collect and preprocess data, federated learning enables secure distributed learning, SMPC supports confidential collaboration, blockchain guarantees immutable audit trails, and robotics executes physical waste handling with verifiable records. This integrated framework fosters trust, ensures regulatory compliance, and accelerates the adoption of AI-driven, transparent, and secure waste management in smart cities [177, 178, 187,188,189].

User acceptance and social adaptation

Integrating Blockchain, IoT, AI, and robotics into smart waste management systems in smart cities poses significant challenges, particularly regarding user acceptance and social adaptation. The success of these technologies' hinges not only on their technical performance but also on the willingness of residents, municipal workers, and other stakeholders to trust, adopt, and engage with digital innovations [25, 51]. Factors such as transparency, privacy, ease of use, and tangible benefits—like improved service reliability and incentives for responsible waste disposal—play a critical role in shaping acceptance [25]. While user-friendly interfaces, real-time updates, and decentralized applications have increased trust—reaching up to 95% in some cases—concerns about data privacy, surveillance, and job displacement continue to generate resistance [25]. Public and worker scepticism often stems from fears of job losses related to automation and invasive surveillance [8]. Additionally, cultural differences, varying digital literacy levels, and unequal access to technology significantly affect how different urban populations adopt and engage with these smart systems [51].

Environmental impact of technology deployment

Integrating Blockchain, IoT, AI, and Robotics into smart waste management systems significantly enhances urban sustainability by enabling real-time monitoring, predictive analytics, route optimization, and AI-driven waste sorting. These technologies collectively increase recycling rates, reduce reliance on landfills, and lower fuel use and emissions by up to 32% and 29%, respectively [8, 42, 180]. Blockchain further advances sustainability by promoting recycling incentives and supporting transparent carbon tracking [181][182].

However, their deployment also introduces environmental challenges. Blockchain networks using PoW algorithms consume substantial energy, while outdated IoT and robotic components contribute to electronic waste. The extraction of raw materials for device production and the infrastructure required for system implementation and maintenance can disrupt ecosystems and strain urban resources. Moreover, the complexity of these integrated systems may lead to environmental trade-offs that undermine their intended benefits [21, 182].

Limited real-world deployment and validation

Integrated solutions that combine Blockchain, IoT, AI, and robotics for smart waste management often remain limited to prototypes, simulations, or small-scale pilots due to their high complexity, cost, and deployment challenges [21, 25, 42]. Researchers and municipalities face challenges in scaling and validating these systems over time, as urban environments vary significantly in terms of infrastructure, governance, and citizen behaviour, which limits the generalizability of findings. Real-world implementations often reveal technical issues, including interoperability problems, latency conflicts between decentralized Blockchain networks and real-time robotic control, and regulatory challenges related to data protection and ethical concerns [21]. The capital-intensive nature of these technologies, combined with uncertain returns on investment, further hinders their adoption, particularly in low- and middle-income regions. A lack of standardized evaluation metrics and long-term studies complicates efforts to assess the effectiveness, scalability, and sustainability of these initiatives. Additionally, social factors such as citizen trust, privacy concerns, and fears of job displacement also influence public acceptance.

FUTURE RESEARCH DIRECTIONS

The integration of Blockchain, IoT, AI, and robotics offers transformative potential for enhancing waste management in smart cities; however, significant challenges and limitations remain. The section below explores the future research that should address these gaps to unlock the full benefits of these technologies and improve waste management systems.

Interoperability frameworks for multi-technology integration

Future research should prioritize the development of robust interoperability frameworks that seamlessly integrate Blockchain, IoT, AI, and robotics in smart waste management systems. These technologies often rely on different communication protocols, data formats, processing capabilities, and security requirements, leading to fragmented and unscalable architectures. To overcome these barriers, researchers must design frameworks that standardize data exchange protocols, unify ontologies, and implement modular middleware capable of supporting real-time communication, context-aware reasoning, and dynamic feedback across heterogeneous components. For instance, synchronizing IoT sensor networks with AI-driven analytics and robotic actuators requires consistent and reliable data flows underpinned by strong interoperability standards. Blockchain can serve as a decentralized trust layer to ensure data integrity and traceability, but its use must account for latency and throughput limitations in real-time applications. Researchers should also explore semantic web technologies, edge computing, and decentralized identity management to enhance cross-domain compatibility while leveraging experimental testbeds and simulations to evaluate system performance under various urban conditions and policy constraints. These efforts will lay the groundwork for scalable, secure, and adaptive smart waste management systems that effectively support sustainable smart cities.

Energy-efficient and green architectures

As smart waste management systems increasingly adopt resource-intensive technologies, such as IoT devices, AI algorithms, Blockchain protocols, and robotic platforms, researchers must prioritize energy efficiency and environmental sustainability in their design and implementation. Developing low-power IoT networks and edge computing architectures that process data locally can reduce energy consumption while maintaining system responsiveness and accuracy. Green AI models optimized for energy efficiency can minimize computational overhead in tasks such as predictive analytics, anomaly detection, and robotic decision-making, underscoring the need for lightweight algorithms and energy-efficient hardware accelerators. To address Blockchain's high energy demands, particularly in public or PoW systems, researchers should pursue eco-friendly consensus mechanisms like PoS, Delegated PoS, or Directed Acyclic Graphs (DAGs), along with hybrid architectures, off-chain storage, and layer-2 scaling solutions for waste tracking and auditing. In robotics, energy-aware designs should incorporate optimized motion planning, efficient actuators, adaptive task scheduling, and renewable power sources such as solar energy. A holistic systems approach that optimizes the interplay among sensors, algorithms, communication protocols, and hardware within real-world urban constraints is essential. By evaluating lifecycle energy use, promoting circular design, and integrating renewable energy sources, researchers can drive the development of truly sustainable and resilient smart waste management systems.

AI-Driven predictive analytics for waste generation

Advanced AI models utilize intensive learning and spatiotemporal analytics to predict waste generation at household, community, and city scales, thereby enhancing resource planning, optimizing collection routes, and guiding the dynamic deployment of robotic systems. Future research should develop and refine AI-driven predictive analytics at fine spatial and temporal scales, applying machine learning techniques, such as time-series forecasting, deep learning, and RL, to diverse data sources, including real-time inputs from IoT-enabled bins, population shifts, seasonal patterns, socioeconomic factors, and consumption trends. These tools enable city managers to proactively adapt collection strategies, allocate resources dynamically, and anticipate waste spikes during events or seasonal peaks, while informing infrastructure design based on projected waste volumes and compositions. To ensure accuracy, scalability, and generalizability across diverse urban contexts, researchers must integrate federated learning and privacy-preserving methods alongside Blockchain for secure, decentralized data sharing and incorporate feedback loops from robotic waste-handling systems to align forecasts with actual disposal behaviors. Advancing this field requires cross-disciplinary collaboration among urban data scientists, environmental engineers, and ethical AI specialists to build technically robust, socially responsible, and environmentally sustainable systems.

Blockchain-enabled incentive mechanisms

Future research should prioritize the design and implementation of Blockchain-enabled incentive mechanisms that promote citizen participation in waste segregation, recycling, and the reporting of illegal dumping. By leveraging smart contracts, these systems can automatically reward environmentally responsible behaviors, such as accurate recycling and timely waste disposal, through transparent, token-based frameworks aligned with sustainability goals. Citizens who consistently adhere to waste sorting guidelines could earn utility tokens redeemable for public services or discounts, with Blockchain ensuring the traceability and integrity of rewards as verifiable proof of contribution. Integrating IoT sensors and AI algorithms can validate user actions in real time, reducing fraud and enhancing accountability, for example, through AI-powered image recognition to assess sorting accuracy or IoT-enabled bins that log disposal activities directly onto the Blockchain. Researchers should also develop decentralized governance models that incorporate community input in setting reward criteria, managing token economies, and auditing system performance. Interdisciplinary studies that integrate behavioral economics, cryptographic protocols, and urban governance are essential to ensure these systems remain equitable, scalable, and adaptable across diverse socioeconomic contexts. Addressing usability, security, and policy integration will be key to transforming traditional waste management into a participatory, transparent, and responsive ecosystem.

Swarm robotics for waste collection and sorting

Swarm robotics, inspired by the collective behavior of social insects such as ants and bees, offers a decentralized and efficient solution for waste collection and sorting in smart cities. Unlike traditional centralized systems, it deploys simple, low-cost autonomous robots that cooperate through local interactions and distributed control, making the system highly scalable, adaptable to dynamic environments, and robust against failures. Equipped with IoT sensors and AI-based perception, these robots can autonomously detect, classify, and sort waste in real time. Integrating Blockchain technology enhances transparency, accountability, and traceability by securely recording waste types, collection times, and sorting performance, while also enabling decentralized coordination and decision-making to reduce reliance on centralized control. Key research challenges include developing energy-efficient coordination algorithms, robust communication protocols for noisy or constrained environments, and real-time adaptability to unstructured urban waste. Researchers must also explore human–robot interaction in public spaces, evaluate the environmental impacts of large-scale deployments, and address ethical and regulatory issues. By merging swarm robotics with Blockchain, IoT, and AI, smart cities can achieve intelligent, autonomous, and sustainable waste management systems.

Cybersecurity and data privacy in integrated systems

Integrating AI, IoT, robotics, and Blockchain into smart waste management systems introduces complex vulnerabilities that require targeted cybersecurity and data privacy research. These interconnected technologies generate and exchange vast amounts of sensitive data, including geolocation, user behaviour, system performance, and predictive analytics, thereby expanding the attack surface and increasing exposure to breaches, malware, unauthorized access, and adversarial AI attacks. To mitigate these risks, researchers must design advanced, multilayered cybersecurity architectures that secure end-to-end communication across devices, networks, and platforms. This involves implementing lightweight encryption for resource-constrained IoT devices, secure key management for decentralized Blockchain nodes, and resilient AI models resistant to data poisoning and inference attacks. By prioritizing privacy-preserving techniques, such as differential privacy, federated learning, and zero-knowledge proofs, researchers can enable secure data sharing and analytics while complying with regulations like the GDPR and emerging smart city policies. Interdisciplinary approaches must incorporate ethical and legal frameworks to ensure socially responsible solutions. As cyber threats evolve, researchers should develop adaptive, AI-driven security systems capable of real-time detection and autonomous mitigation. Strengthening cybersecurity and data privacy in these integrated systems is critical to building trust, resilience, and long-term sustainability in smart waste management and the broader smart city ecosystem.

Real-time decision-making with edge and fog computing

Integrating Blockchain, IoT, AI, and robotics into smart waste management requires the timely collection, processing, and analysis of data from distributed sensors and autonomous devices. Traditional cloud-centric architectures often fall short due to latency, bandwidth constraints, and privacy concerns, limiting their effectiveness in real-time, dynamic environments. To overcome these issues, edge and fog computing enable localized data processing near the source, such as smart bins, robotic collectors, and IoT gateways, facilitating faster decision-making and reducing dependence on centralized cloud servers. Fog computing adds an intermediate layer between edge devices and the cloud, supporting hierarchical data management, enhanced scalability, and efficient resource allocation. Researchers should design integrated frameworks that combine edge and fog nodes with Blockchain to ensure secure, traceable, and decentralized real-time operations. Embedding AI algorithms at these layers enables predictive analytics, anomaly detection, and adaptive control of robotic waste systems, allowing for immediate responses to overflow, traffic congestion, or hazardous materials. Future efforts must address the limitations of edge devices, including limited computational power, high energy demands, and interoperability issues among heterogeneous components. Developing lightweight AI models and energy-efficient communication protocols will be crucial for maintaining performance without compromising operations. By reducing reliance on cloud infrastructure and securing microtransactions with lightweight Blockchain clients, edge and fog computing can significantly enhance the scalability, responsiveness, and intelligence of smart waste management systems in smart cities.

Circular economy models and smart recycling

Integrating Blockchain, IoT, AI, and robotics into smart waste management systems unlocks powerful opportunities to embed circular economy principles within urban sustainability efforts. Circular economy models aim to minimize waste and maximize resource efficiency by promoting reuse, repair, remanufacturing, and recycling within closed-loop systems. To realize this vision, researchers must develop integrated frameworks that track, verify, and optimize material flows in real time throughout the waste lifecycle. Blockchain ensures transparency and accountability by securely recording data on the origin, composition, and processing history of waste. When paired with IoT-enabled sensors and smart bins, it facilitates precise segregation and collection of recyclables, improving both the quality and quantity of recovered materials. AI analyzes complex data to forecast waste generation, optimize collection routes, and detect contamination, thereby enhancing efficiency and reducing operational costs. Robotics automates sorting processes, increasing speed and accuracy while minimizing human exposure to hazardous materials. Researchers should also design decentralized circular economy platforms that utilize Blockchain-based networks to connect producers, consumers, waste managers, and policymakers, and incorporate incentive mechanisms, such as tokenization, to promote recycling and sustainable consumption. At the same time, scholars need to evaluate the socioeconomic impacts of these systems, including issues of accessibility, equity, and behavioural change, to ensure inclusive outcomes. Addressing challenges related to scalability and interoperability remains critical for adapting these systems across diverse urban contexts. Moreover, integrating AI with smart contracts can automate and enforce circular practices, such as deposit-return schemes, waste-to-energy conversions, and Blockchain-verified recycling chains, ultimately building transparent, resilient, and efficient waste management systems for smart cities.

Digital twin models for urban waste management

Digital twins serve as powerful tools for simulating waste generation, optimizing collection logistics, and predicting infrastructure wear and tear. By integrating real-time IoT data with AI-driven simulations, researchers can forecast disruptions and enhance maintenance strategies. As dynamic virtual replicas of physical systems, digital twins enable continuous monitoring, simulation, and optimization through real-time data exchange with their physical counterparts. In smart waste management, these technologies can be combined to create a comprehensive, real-time representation of the entire waste lifecycle—from collection and transportation to processing and disposal. IoT sensors in bins, vehicles, and facilities provide live data that AI algorithms use to predict waste volumes, optimize routes, and detect bottlenecks or system failures. Blockchain ensures data transparency and integrity, while robotics automates tasks like dynamic routing for autonomous vehicles and real-time control of sorting systems. To fully leverage this potential, researchers must develop scalable, interoperable digital twin architectures that integrate diverse data sources and adapt to evolving urban environments. They should also develop predictive models that incorporate social, environmental, and economic factors to support sustainability-driven decisions. Pilot projects in varied urban contexts will be crucial for evaluating the practical impact of digital twins and shaping future innovations. Advancing these technologies will enhance the agility, efficiency, and sustainability of urban waste systems, supporting the development of resilient, intelligent, and smart cities.

Socio-technical frameworks for community engagement

Effective community engagement drives the success of smart waste management systems that combine Blockchain, IoT, AI, and robotics. Future research should develop comprehensive socio-technical frameworks that integrate social, cultural, and behavioral factors with technological innovations to involve diverse stakeholders—residents, local authorities, waste operators, and technology providers—in the design, deployment, and governance of these solutions. Researchers need to apply participatory design methods tailored to local contexts, foster trust through transparent data sharing and privacy safeguards enabled by Blockchain's accountability, and create behavioural incentives using IoT-powered real-time feedback, AI-driven personalization, and robotic convenience. They must also promote equity by crafting inclusive, culturally sensitive engagement strategies that reach marginalized communities, while embedding governance models that facilitate collaboration among public, private, and community actors and support adaptive policies. By blending these social and technical elements, future studies can unlock the full potential of these technologies to build sustainable, inclusive, and resilient smart cities through more innovative waste management.

Policy-aware AI and regulatory compliance engines

AI systems must dynamically align with evolving municipal, national, and international environmental regulations by developing policy-aware models that leverage natural language processing and knowledge representation to interpret, adapt to, and enforce waste management rules within complex ecosystems that combine Blockchain, IoT, AI, and robotics. These AI engines will continuously monitor legal updates, translate regulations into actionable directives, and ensure data collection, processing, and waste handling comply with environmental, privacy, and safety standards. By integrating AI with Blockchain's transparency and immutability, the system enables real-time auditing and verifiable compliance, fostering trust among regulators, citizens, and service providers. Robotics embedded in these platforms will autonomously adjust operations, such as waste sorting and transportation routes, to maintain compliance without human intervention. Researchers must tackle challenges in designing flexible, interpretable AI that manages ambiguous or conflicting regulations, integrates compliance across diverse IoT and robotic devices, and builds scalable frameworks that respect jurisdictional differences while ensuring interoperability. Advancing these policy-aware AI and compliance engines will optimize smart waste management, uphold legal and ethical standards, and support sustainable development goals in smart cities.

Integrating blockchain, IoT, AI, and robotics into waste management systems presents significant regulatory and ethical challenges that require proactive attention to ensure lawful, transparent, and socially responsible operation. Two primary areas of concern are data protection and privacy compliance, including adherence to the EU GDPR, as well as ensuring algorithmic fairness in AI-driven waste sorting. IoT-enabled waste management systems use dense networks of smart bins, RFID tags, environmental sensors, and GPS trackers to gather data on waste type, volume, origin, and disposal patterns. Although most of this data supports operational efficiency, certain datasets, such as location-linked disposal habits, may constitute personal data under the GDPR, especially if they can be linked to identifiable households or individuals. To address these concerns, systems must implement several compliance measures. First, IoT devices should adhere to the principles of data minimization and purpose limitation, collecting only the data necessary for operational efficiency. For example, systems can store aggregate bin-level data rather than individual household records unless fine-grained tracking is essential. Second, sensitive datasets must undergo irreversible anonymization or robust pseudonymization before being stored on blockchain or used for AI training, reducing the risk of re-identification. Third, data collection and processing should rely on a lawful basis under GDPR, such as legitimate interest for city services or explicit consent from participants in pilot programs. Fourth, blockchain applications must adopt privacy-preserving approaches, such as storing hashed references or off-chain encrypted records, since storing raw personal data on an immutable ledger could violate the GDPR's "right to be forgotten." Finally, clear data governance and accountability structures should define roles for data controllers, such as municipal authorities, and processors, such as technology vendors, supported by GDPR-compliant data-sharing agreements.

AI-powered robotics play a central role in automating waste classification, prioritizing recycling streams, and optimizing collection routes. However, AI models can introduce bias if their training data or operational parameters disproportionately disadvantage certain communities or stakeholders. For instance, route optimization algorithms might unintentionally deprioritize waste collection in low-income neighborhoods if trained on biased data regarding service frequency. To ensure fairness, operators should regularly audit datasets for geographic or socioeconomic underrepresentation and retrain models using balanced datasets to address these issues. They should also incorporate explainable AI techniques to make sorting and routing decisions interpretable for operators, policymakers, and the public. Conducting ethical impact assessments before deployment helps identify potential discriminatory effects on service quality, recycling incentives, or economic outcomes across demographic groups. Maintaining human oversight over critical AI decisions ensures that errors do not lead to environmental harm or public dissatisfaction.

Beyond GDPR and fairness, systems must comply with local waste management laws, environmental regulations, and occupational safety standards. Robotic systems should adhere to ISO standards for safety and interoperability to ensure optimal performance and reliability. Blockchain applications must comply with emerging digital asset and data sovereignty laws. IoT devices should meet cybersecurity requirements under frameworks such as the EU Cybersecurity Act.

Finally, sustaining public trust requires a multi-stakeholder governance approach. Engaging citizens through public consultation ensures transparency around data usage, privacy safeguards, and AI-driven decision-making. Publishing regular transparency reports can provide detailed information on data processing practices, algorithmic performance, and efforts to mitigate bias. Policymakers and operators should also commit to sustainability and equity, ensuring that efficiency gains do not compromise environmental protection or equitable service distribution.

Waste valorisation through robotic AI

AI-powered advanced robotics can revolutionize waste valorization by automating and optimizing the identification, sorting, and processing of various waste streams, including organic, recyclable, hazardous, and electronic waste. Researchers enhance precision in tasks such as electronic disassembly, metal extraction, and organic waste preparation for bioenergy by developing sophisticated AI algorithms and integrating robotic manipulators with advanced sensors and computer vision capabilities. Machine learning models, trained on extensive datasets, enable these systems to adapt in real time to changing waste compositions and contamination. By combining robotic capabilities with Blockchain and IoT technologies, they ensure traceability, transparency, and continuous process monitoring. Future research must tackle challenges related to energy consumption, cost-effectiveness, scalability, and environmental impact to maximize sustainability. Advancing AI-driven robotics transforms waste management from simple disposal into efficient resource recovery and value creation, supporting the goals of sustainable smart cities and a circular economy.

Self-healing and adaptive waste networks

IoT-enabled waste systems must leverage adaptive AI algorithms to detect anomalies such as sensor failures or route blockages and promptly trigger robotic or system-level countermeasures. Future research should develop self-healing, adaptive waste management networks that seamlessly integrate Blockchain, IoT, AI, and robotics to autonomously detect, diagnose, and recover from faults or inefficiencies in real time, ensuring uninterrupted operation within the dynamic environments of smart cities. These networks continuously monitor system health through advanced AI algorithms paired with IoT sensors, enabling robotic units and smart bins to identify malfunctions, communication issues, or blockages. AI-driven predictive analytics anticipate failures and automatically initiate corrective actions, such as rerouting collection paths, recalibrating sensors, or alerting maintenance teams, without requiring human intervention. The system dynamically reconfigures itself to adapt to shifting waste patterns, seasonal changes, or urban development by optimizing routing, resource allocation, and robotic deployment using real-time IoT data secured through Blockchain. Blockchain maintains a secure and immutable record of system changes, thereby enhancing auditability and stakeholder trust. By integrating these self-healing and adaptive features, smart waste management systems achieve greater resilience, sustainability, and autonomy, enabling them to address the complex challenges of evolving urban environments.

Multi-stakeholder governance models

Effective governance is crucial for deploying and managing complex, technology-driven smart waste management systems. Future research should develop robust multi-stakeholder governance models that foster collaboration, transparency, and accountability among municipal authorities, technology providers, waste management companies, local communities, environmental regulators, and end-users. These models must balance decision-making power to ensure equitable participation and representation. Researchers should harness Blockchain's transparency and immutability to build trust through secure, auditable transaction records while addressing data privacy, access control, and regulatory compliance challenges to maintain stakeholder confidence. Governance policies must clearly define roles, responsibilities, and ethical boundaries for IoT- and AI-driven dynamic data flows and automated decisions. Coordinating the physical interaction of robotics with urban environments requires protocols that address safety, liability, and public acceptance. Researchers should design adaptive governance frameworks that evolve in tandem with technological advances and diverse urban contexts, incorporating conflict resolution mechanisms, incentives for sustainable behaviors, and integration with existing legal and institutional frameworks. By conducting case studies and pilot projects, they can uncover best practices and real-world challenges. Furthermore, exploring Blockchain-enabled decentralized autonomous organizations will facilitate multi-stakeholder collaboration in smart waste policy-making, budgeting, and execution, unlocking the full potential of integrated technologies to support sustainable, inclusive, and resilient smart city ecosystems.

Cross-domain integration for holistic urban sustainability

Future research should focus on advancing cross-domain integration to achieve holistic urban sustainability by developing frameworks that enable seamless interoperability and data exchange among critical urban systems such as waste management, energy, water, transportation, and public health. By integrating smart waste management data with energy grids, cities can optimize energy recovery from waste processing. Connecting waste sensors with traffic management systems can also improve collection routes, thereby reducing emissions and congestion. Researchers must design AI models that analyze combined datasets across various sectors to predict more accurately and mitigate environmental and social impacts more effectively. Additionally, leveraging Blockchain as a decentralized platform can secure transparent data sharing among municipal authorities, service providers, and citizens, fostering collaborative decision-making and accountability. To build scalable, flexible, and adaptive systems that support real-time analytics and automated responses, researchers must address challenges including heterogeneous data standards, privacy concerns, and computational complexity. By moving beyond isolated solutions, this integrated approach will optimize resource use, minimize environmental footprints, and enhance quality of life through shared AI models and Blockchain infrastructure, driving synergistic urban sustainability across smart city systems.

Sixth generation (6G) for IoT in smart waste management

Anticipated in the 2030s, 6G wireless communication is expected to revolutionize large-scale IoT deployments in smart waste management, surpassing 5G with ultra-low latency (<1 ms), peak data rates exceeding 1 Tbps, sub-centimeter localization, and support for up to 10^7 devices per square kilometer. These capabilities will enable hyperconnected waste systems where IoT sensors, robotic collectors, AI-driven analytics, and blockchain-based data sharing operate in near real-time with minimal human intervention. Dense sensor networks embedded in bins, trucks, recycling plants, and transfer stations will continuously monitor fill levels, waste composition, temperature, and hazardous materials, transmitting rich multimodal datasets, including high-resolution images, chemical spectra, and environmental parameters, to AI platforms without bandwidth constraints. Leveraging terahertz (THz) frequencies, intelligent reflecting surfaces (IRS), and integrated space–air–ground–sea networks, 6G will maintain seamless connectivity in challenging environments such as underground tunnels or remote landfills. Blockchain smart contracts will automatically trigger robotic collection or optimize routes, while AI and robotics enable autonomous fleets to self-coordinate, perform predictive maintenance, and follow energy-efficient paths. Key research challenges include developing energy-efficient protocols to extend the battery life of IoT devices, scalable post-quantum security architectures, edge intelligence for reduced latency and bandwidth consumption, and sustainable infrastructure for high-frequency 6G hardware. By addressing these issues, 6G-powered IoT ecosystems will drive autonomous, decentralized, and circular waste management in smart cities, enhancing operational efficiency, environmental sustainability, and citizen well-being.

Quantum-inspired algorithms for route optimization

Future research on smart city waste management can leverage quantum-inspired algorithms to optimize collection routes more efficiently than classical methods. By drawing on quantum principles, such as superposition, entanglement, and probabilistic state transitions, while running on conventional hardware, these algorithms, including quantum annealing heuristics and quantum-inspired evolutionary algorithms (QIEA), solve NP-hard problems like the Capacitated Vehicle Routing Problem (CVRP) and Dynamic Waste Collection Routing with reduced computational time. In a blockchain–IoT–AI–robotics framework, IoT-enabled smart bins continuously transmit real-time fill levels, geolocation, and environmental data to a central system. In contrast, blockchain ensures secure, tamper-proof sharing across stakeholders. AI models predict waste generation patterns and dynamically assign collection priorities, and quantum-inspired optimization modules process this data to generate near-optimal adaptive routes for autonomous or semi-autonomous collection units. Unlike classical metaheuristics, these algorithms explore broader solution spaces through quantum-like parallelism, thereby minimizing the risk of local optima and enabling multi-objective optimization across various factors, including travel distance, fuel consumption, traffic congestion, load balancing, and emissions. By incorporating stochastic traffic models and temporal constraints, they adapt to dynamic urban environments, enhancing real-time decision-making, operational efficiency, and environmental sustainability, particularly when deployed at the edge. As quantum hardware advances, these algorithms can transition to quantum processors, further accelerating performance and positioning smart cities at the forefront of technology-driven, sustainable waste management.

Policy-oriented recommendations

The successful deployment of blockchain-based waste tracking systems in smart cities depends on aligning technological innovation with well-designed policy frameworks. Future research should investigate how technical solutions interact with governance mechanisms, with a focus on incentives, standards, and regulatory oversight that promote adoption, scalability, and societal impact. To drive innovation and scale, governments and municipal authorities can implement incentive structures that encourage private-sector participation in blockchain-enabled waste management. For example, they can offer tax credits or capital subsidies to waste management companies, logistics providers, and recycling plants that adopt blockchain-based tracking systems. Public–private partnership models can also play a critical role, where public agencies fund initial infrastructure, such as IoT sensor networks and blockchain nodes.

In contrast, private operators manage and optimize operations. Performance-based incentives can link rewards to measurable outcomes, including increased recycling rates, reduced landfill use, or verifiable reductions in illegal dumping through blockchain audit trails. Additionally, innovation grants and challenge funds can support startups and small and medium-sized enterprises developing blockchain-integrated robotics, AI-based sorting algorithms, and IoT waste-sensor technologies, providing seed funding and research and development resources. The lack of clear policies often slows the adoption of emerging technologies in municipal systems. Research should focus on developing adaptive regulatory frameworks that ensure data security, transparency, and accountability, while remaining flexible enough to accommodate technological advancements. Data governance policies must define rules for the ownership, access, and sharing of waste tracking data generated by IoT devices and stored on blockchain, ensuring compliance with privacy laws and interoperability standards. Developing national or regional interoperability standards can enable seamless integration between blockchain-based waste tracking systems across cities and service providers. Governments should also establish legal recognition for blockchain-based smart contracts governing waste collection agreements, recycling commitments, and penalties for non-compliance. Integrating blockchain records with environmental regulations can support automated compliance reporting, auditing, and enforcement. Meanwhile, implementing minimum cybersecurity benchmarks for blockchain nodes and IoT devices can prevent tampering, data breaches, or service disruptions.

Future studies should explore the intersection of policy and technology from multiple perspectives. Researchers can develop impact assessment models to evaluate the cost–benefit balance of blockchain-enabled waste tracking compared to conventional systems, considering economic, environmental, and social factors. Investigating dynamic pricing and tokenization can reveal how blockchain-based tokens or credits may reward households, industries, and businesses for responsible waste disposal within circular economy frameworks. Cross-border waste tracking also warrants attention, with international blockchain registries aligned with Basel Convention guidelines to curb illegal transboundary waste movement. Moreover, designing citizen engagement policies can facilitate participatory governance, enabling residents to access blockchain dashboards, monitor waste management performance, and contribute to informed decision-making.

As blockchain-based waste tracking matures, research should focus on harmonizing standards and best practices to ensure consistency and effectiveness. Establishing international consortia can facilitate cross-country research networks that test the integration of blockchain, IoT, AI, and robotics under diverse regulatory contexts. Collaborating with organizations such as ISO, ITU, and UNEP can help define technical and ethical standards for waste data on distributed ledgers. Ultimately, establishing knowledge transfer mechanisms can ensure that lessons learned from pilot projects in early-adopting cities inform and guide implementation in later-adopting municipalities.

How can federated learning improve AI-driven waste prediction in low-bandwidth environments?

Federated learning provides an effective approach for AI-driven waste prediction in low-bandwidth environments by enabling decentralized model training and minimizing data transmission. Local devices, such as smart bins and edge sensors, train models on-site and transmit only model updates—not raw data—to a central server, significantly reducing bandwidth demands [182, 183]. Advanced federated learning frameworks, such as FedADC, further reduce communication overhead through techniques like knowledge distillation and mutual conditional learning, while maintaining high classification accuracy [183]. Additionally, over-the-air aggregation and analog transmission reduce latency and bandwidth usage, even under noisy or unreliable network conditions [182]. By dynamically selecting participating devices and managing bandwidth allocation, federated learning optimizes resource use and enhances learning performance over time, adapting efficiently to fluctuating network conditions. Federated learning-based waste classification systems demonstrate strong performance across multiple dimensions. They achieve high accuracy—up to 9.9%—while outperforming traditional centralized approaches, even when handling heterogeneous and distributed data [184, 185]. By processing data locally, these systems protect sensitive information, enhance privacy, and comply with regulatory requirements, which is particularly crucial in public waste management [182]. Additionally, federated learning frameworks are adaptable to both urban and rural settings, enabling scalable deployment without overloading network infrastructure [182-184].

CONCLUSION

The fusion of Blockchain, IoT, AI, and Robotics is transforming how smart cities tackle the complex challenges of waste management. IoT-enabled sensors collect real-time data to monitor environmental conditions, providing continuous visibility throughout the entire waste generation and management cycle. AI algorithms analyze this data to deliver predictive insights, optimize waste collection routes, and support informed decision-making, thereby reducing operational inefficiencies and minimizing environmental impact. Robotics automates labour-intensive tasks, such as waste sorting, thereby enhancing worker safety and improving system reliability. Meanwhile, Blockchain creates a decentralized, transparent ledger that fosters accountability and trust among all stakeholders by enabling secure data sharing, incentivizing recycling through tokenization, and recording verifiable transactions that promote a circular economy within urban ecosystems.

Together, these technologies converge to build intelligent, responsive, and scalable waste management infrastructures aligned with urban sustainability goals, resource efficiency, and climate resilience. However, unlocking their full potential demands overcoming technical, regulatory, and socio-economic challenges. Issues such as data interoperability, high energy consumption, cybersecurity vulnerabilities, ethical concerns around AI and robotics deployment, and public acceptance require urgent attention. Future research and policy must focus on establishing open standards, ensuring privacy-preserving data architectures, encouraging cross-sector collaboration, and promoting inclusive innovation that benefits all urban populations. Pilot projects and longitudinal studies remain essential for empirically validating the performance, scalability, and socio-environmental impact of integrated smart waste management systems.

In conclusion, integrating these emerging technologies does more than advance waste management technology it completely reimagines urban waste systems. As cities worldwide face increasing environmental pressures and growing populations, this multidimensional approach offers a practical pathway to creating sustainable, equitable, and resilient smart cities for the future.

AUTHOR CONTRIBUTIONS

A. G. contributed to the conceptualization, supervision, and overall project administration. D. A. and M. M. M. were responsible for the literature search, data curation, drafting the original manuscript, validation, and critical editing. I. A. prepared the tables, figures, and assisted with manuscript revision. M. D. provided resources, contributed to the critical review of the manuscript, and approved the final version. All authors have read and agreed to the published version of the manuscript.

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CONFLICT OF INTERESTS

The authors declare that they have no conflict of interest.

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