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A Comprehensive Review of Smart and Sustainable Waste Management Using Artificial Intelligence, Internet of Things, and Robotics

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Abstract

Urbanization and population growth have made waste management more challenging in urban areas such as parks, streets, and public transport. Traditional waste collection requires significant manual labor and is inefficient, expensive, and poses health hazards to sanitation workers. Recent advances in robots, Artificial Intelligence (AI), and the Internet of Things (IoT) have enabled autonomous and intelligent waste management systems that can detect, collect, and separate waste. This paper reviews intelligent robotic solutions for automated waste collection and separation. Key subsystems are discussed, including perception, navigation, manipulation, sorting, and IoT for waste management data generation. Sensor technologies such as ultrasonic, inductive, and moisture sensors, along with machine vision and deep learning algorithms for waste classification, are examined. Communication architectures using Global System for Mobile Communications (GSM), Global Positioning System (GPS), and mobile applications for real-time tracking and operation are also discussed. Existing automated systems are reviewed, and despite significant progress, long-term challenges remain related to energy efficiency, outdoor operation, and large-scale deployment. The review further identifies critical research gaps in system-level integration, autonomy, and scalability, and highlights future directions toward unified AI–IoT–robotic frameworks, energy-aware designs, and adaptive navigation strategies for sustainable and smart urban waste management.

Keywords: Autonomous waste management; Intelligent robots; Internet of Things (IoT); Artificial intelligence (AI); Waste segregation.

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1. Introduction

The management and disposal of solid waste represent both environmental and operational challenges in contemporary urban environments.[1-3] Changes associated with rapid industrialization, urbanization, and increased population sizes have led to unprecedented amounts of solid waste generated daily in public space.[4,5] Many of the activities that happen in parks, bus stations, railway stations, campuses, marketplaces, and many other usual public spaces generate extra solid waste, litter, and debris beyond what is already common. Current waste collection and disposal methodologies remain largely labor-intensive and are typically governed by fixed or irregular cleaning schedules; such approaches are often suboptimal and inconsistently executed, resulting in inefficient resource utilization.[6,7] As the organic and inorganic waste heaps and volumes grow, a traditional approach to cleaning is not successful and cannot keep up with the need for cleansing.[8] Waste collection often becomes necessary only after bins overflow and litter spreads into surrounding areas. Such unmanaged solid waste is

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aesthetically displeasing and poses serious ecological and public health risks, including the spread of infectious diseases, blocked drainage systems, and contamination of soil and water resources.[9-11] Therefore, the current crisis around solid waste management and disposal must shift more toward automation where we rely less on human participation, yet are more efficient and sustainable.[12,13]

The rapid advancements in robotics, automation, artificial intelligence (AI), and the Internet of Things (IoT) have made the development of a new form of useful intelligent systems that can perform complicated tasks autonomously.[14-18] Autonomous robots that can perceptually sense their environment, make informed decisions, and then act on those decisions, are being increasingly used in various industries and markets, including manufacturing, logistics, healthcare, and agriculture.[19,20] The use of robots with autonomous technology in waste management is relatively new but swiftly advancing.[21] Autonomous waste-collecting robots have multiple sensors, embedded processors, and AI-based autonomous decision-making capabilities, which allow them to detect, collect, classify, and process waste materials more efficiently than humans.[22,23] Autonomous waste-collecting robots are particularly well suited for public spaces characterized by high and unpredictable waste generation, where continuous cleanliness is essential and manual cleaning may lead to inefficiencies or disruptions. Their deployment enables uninterrupted waste management operations, thereby maintaining hygienic conditions and improving overall environmental quality. An autonomous waste-collecting robot is a developing area of intelligent robotic waste management as it relates to fuzzy robotic perception, incorporated IoT networks, and all aspects of autonomous waste collection and segregation.[24]

Despite widespread implementation, existing waste management systems exhibit numerous operational and structural limitations. Manually collecting waste is laborious, inefficient, and oftentimes unsafe.[25] Waste collectors are often exposed to dangerous materials, sharp objects, and pathogens with no protective gear, leading to significant hazards to health.[26-29] In addition, manual classification of waste is rarely effective at the collection point, resulting in recycling waste mixed in with non-recycling waste, which undermines recycling efforts and increases overall landfill volume. Furthermore, irregular schedules and lack of monitoring systems exacerbate the problems associated with waste control. All of these factors can serve as barriers to realizing an automated solution that can efficiently collect waste, actively monitor disposal practices in real time, and classify waste intelligently without the assistance of humans. The incorporation of AI and IoT into waste management has numerous benefits and paradigm shifts.[30-32] AI machines have perceptive and learning capabilities, so AI machines make predictions, detect, classify, and distinguish objects of waste using computer vision, sensor fusion, and pattern learning algorithms.[33] IoT provides connectivity that enables bi-directional communication between robots, operators, control centers, and mobile devices to monitor, track, and ascertain decisions in real-time, thus, ensuring maximum efficiency.[34,35] Waste management robots can detect and learn about the objects comprising waste using ultrasonic sensors, inductive proximity sensors, moisture sensors, and RGB cameras, allow the robot to distinguish between waste such as whether it is dry, wet or metallic and make accurate real-time sorting.[18,36] Adding GPS and GSM modules can further improve operational efficiency and effectiveness as it provides tracking of the location tracking and updates the robot status live and alerts for abnormalities such as fault, full bin or low battery.[37] The emergence of these technologies and their use in waste management could upend traditional processes to more innovative, coordinated, and sustainable approaches.

In the last few years, various researchers and developers have attempted different robotic systems to collect and sort waste. These robots function with a combination of data from sensors and AI-based decision models that allow them to detect and pick up waste.[38] Early systems primarily designed

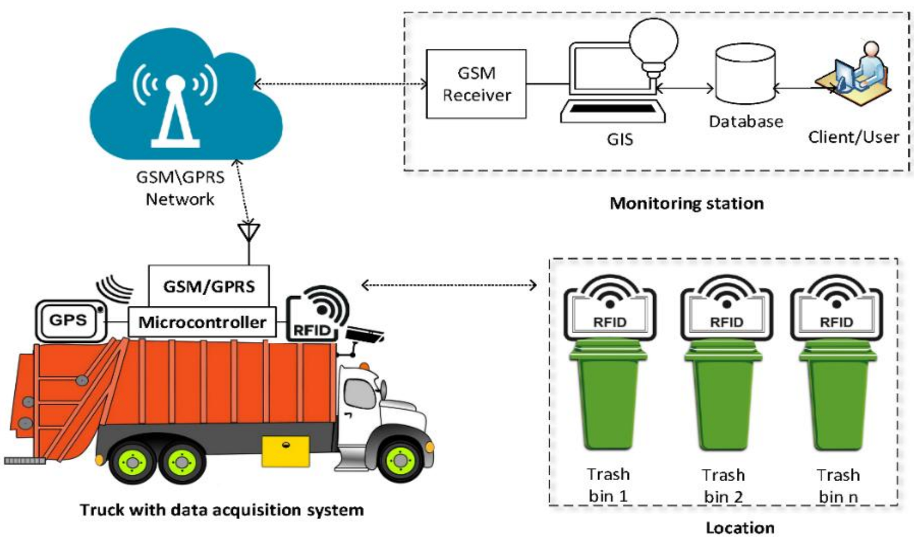

Fig. 1: IoT based solid waste handling system. Reproduced from [37].

for mobile waste collection in urban streets include DustCart developed in Europe,[39] which relied primarily on human–robot interaction. Later systems started to include IoT-based modules to allow for remote monitoring and report on the status of the robot. More recently, systems have utilized computer vision, powered by AI, to improve sample identification of waste and refuse. For instance, convolutional neural networks (CNNs) and object detection models such as YOLO and MobileNet, may be used to classify waste materials directly from an image from the onboard camera of the robot.[40] These systems are a notable improvement because they make the detection of waste significantly more accurate, and allow a robot to handle different types of waste in different environments, both with and without the assistance of a human operator. However, despite numerous advances in technologies, most existing robotic waste collection solutions still do not possess full autonomy. Many robotic waste collection solutions still hybrid forms, relying on operators to direct the solution, predefined route paths, and limited ability to adapt to working environments; therefore, these solutions cannot easily be implemented in public engaged spaces.

Fig. 2: Conceptual architecture of an intelligent waste management system incorporating AI-based decision making, IoT sensing, and robotic sorting mechanisms.

Although significant progress has been made in robotic and IoT-enabled waste management, several challenges still hinder the large-scale deployment of fully autonomous waste collection robots.[41] Power management remains a major limitation, particularly in achieving energy-efficient operation and integrating renewable energy sources such as solar charging. Terrain adaptability is another challenge, as most robots are optimized for flat surfaces, whereas real-world environments include slopes, curbs, and wet conditions. In addition, maintenance requirements, system durability, and deployment costs affect scalability and return on investment. Ongoing research in lightweight materials, efficient motor control, and artificial intelligence is expected to progressively address these challenges. This review examines the technological foundations, current deployments, and research trends in robotic waste management, with a focus on perception, navigation, sorting, and communication systems. It also highlights existing research gaps and outlines future research directions toward sustainable urban sanitation.

2. Literature survey

2.1 Review & taxonomy studies

Maghsoudi *et al*.[42] retrieved 9,095 articles on waste management published since 2000 from the Web of Science (WoS) database. Based on these articles, a keyword network comprising 17,808 unique keywords (nodes) and 79,763 links was constructed. To identify the major research areas in waste management, a community detection technique was applied to the keyword network, resulting in the identification of ten main communities. These communities, named according to waste management characteristics and waste types, collectively represent more than 90% of the overall waste management research. Nižetić *et al*.[42] provide a collection of publications concerning innovative technology towards dealing with the challenges of a modern city, focusing primarily on innovations in waste management. The authors do this through a non-systematic review using relevant conference papers on sustainability and efficiency of resource utilization. The paper discusses the key connections between waste management systems (WMS), recycling and circular economy, as well as plastic pollution. However, research is limited in its extensive or systematic review and lacks consistent criteria for selecting studies in addition to no formal structure meta-review can be established in the future. Rodríguez-Guerreiro *et al*.[43] conducted a Scopus-based literature review on waste management in higher education institutions, analyzing 293 publications across waste generation and composition, composting, food waste, and edible food waste. The results show a strong increase in research after 2017, with composting receiving the greatest attention, alongside studies on zero-waste and waste minimization strategies. Hariyani *et al*.[44] adopted a systematic review methodology in accordance with the PRISMA guidelines, encompassing the stages of identification, screening, eligibility, and inclusion. Relevant studies were retrieved from the Scopus database using keyword combinations related to waste management and treatment technologies within titles, abstracts, and keywords. Following the removal of duplicates, non-English, and inaccessible records, successive screening and full-text evaluation resulted in a final dataset of 392 articles published between 2000 and 2025, which were subjected to in-depth analysis. Dawal *et al*.[45] reviewed 69 studies published between 2018 and 2024 using the PRISMA methodology to examine the application of artificial intelligence, particularly machine learning and deep learning techniques, in municipal solid waste management. The review highlights the potential of AI to improve decision-making, resource recovery, and circular economy practices, while also identifying challenges related to data availability, quality, and interdisciplinary integration in achieving sustainable urban waste management aligned with the UN SDGs. Pardini *et al.*[46] provide a complete review of research on IoT architecture and communication protocols in waste management systems. This study examined a series of research papers concerning IoT framework systems for monitoring smart bins and urban waste. In conclusion, the authors examined how while technological solutions are improving, few IoT systems really add any extra capability for citizen engagement (which is extremely important to waste collection time and costs). The gap in the literature is that no design was centered around the human aspect to engage the community. Anuardo *et al*.[47] employed a combined research methodology integrating literature review and content analysis to examine waste management research. The literature review facilitated the identification of research gaps, while content analysis enabled the detection of publication trends, thereby supporting the qualitative development of policies, initiatives, and a conceptual framework for advancing waste management research. Sahu *et al*.[48] reviewed 15 studies examining the application of emerging industrial technologies for waste sorting in urban systems in India. Using content analysis of scientific articles and technical reports, the authors identified several significant technological innovations in waste sorting practices. However, the study was geographically limited to Indian metropolitan areas, which the authors acknowledged as a key limitation, restricting cross-country comparison and broader generalization of findings. Akram *et al.*[49] provided a review of ICT applications in waste management with a focus on communication protocols and energy-efficient IoT deployments. The authors highlighted the significance of selecting the appropriate wireless communication technology in order to optimize the operational life of smart bins, while also recognizing blockchain as a significant enabler of integrating various stakeholders in a waste-management network. Despite these contributions, it still seems that there is a gap in the research about how well these ICT have been integrated in practice from a real-world implementation perspective. Rajeb *et al*.[50] conducted a taxonomy-driven review of Internet of Things (IoT) applications in smart cities by retrieving peer-reviewed journal articles from the Scopus database, selected for its extensive coverage and reliable indexing of high-impact international publishers. To maintain methodological rigor and ensure the quality of the synthesized evidence, the study deliberately limited its scope to journal articles, notwithstanding ongoing debates in meta-analysis literature regarding publication type selection, as this strategy was considered most appropriate for developing a robust and comprehensive taxonomy of IoT-based smart city research.

Ramirez *et al.*[51] included a section related to innovative waste systems in their review of articles related to IoT in smart cities. They conducted a review of 22 articles related to the emergence of IoT for smart bins. This review provided a broad overview of IoT in the smart city ecosystem, but did not provide much technical detail related to innovative waste systems. The gap in research was that there are no technical specifications for in depth comparisons to facilitate use in practice Concari *et al.*[52] provided a bibliometric and text-mining analysis of 2061 publications assessing citizen recycling behaviors. They employed data mining software to identify emerging trends and thematic associations, and concluded that local city innovative policies were a major influence on citizen recycling behaviors. The research gap noted in the study was the lack of connections between behavioral evidence and practical areas of technology in innovative waste systems. D'Amico *et al.*[53] provides a review that looks at the digitalization of resource loops in smart cities, focusing specifically on "urban metabolism circularity." The authors reviewed ICT-based tools that digitalize the circulation of materials from consumption to waste and provided case studies for illustration. The authors found that ICT can be helpful in hastening the adoption of circular economy practices, although the authors mentioned a lack of empirical evidence to support their assertions. The gap in the study is a (very) limited number of operational examples that have shown any measurable environmental impact, specifically referencing the need for operational implementations to verify the outcomes of the urban metabolism framework. Zoumpoulis *et al.* [54] presented a comprehensive review of waste collection bins with smart capabilities, highlighting their critical role in modern urban environments and sustainable waste management systems. The study systematically analyzed 79 selected articles from an initial pool of more than 1,400 publications, focusing on state-of-the-art smart bin technologies and advanced functionalities such as automated material separation and integrated control mechanisms. Although a broadly accepted definition of smart bins exists—characterizing them as waste containers equipped with features such as fill-level monitoring and IoT connectivity—the review identified substantial gaps in the existing literature. In particular, limitations were observed in material separation practices, including automated waste segregation, as well as in the maturity and consistency of conceptual frameworks, which collectively hinder efficient resource recovery and the realization of circular economy models. Furthermore, the analysis revealed a lack of standardization and uniformity in automation approaches, with existing studies proposing diverse solutions that exhibit varying strengths and limitations. The absence of a unified and scalable framework underscores the need for consolidated design principles to advance smart bin technologies and address sustainability challenges in future smart city deployments.

2.2 IoT architectures & smart-bin designs

Idwan *et al.*[55] proposed a waste management system based on IoT technology to enhance the scheduling and routing of waste collection vehicles within a metropolitan area. The study implemented a two-phase metaheuristic approach that utilized a Genetic Algorithm (GA) to reduce collection distance and the number of trucks. The study conducted two trials, an IoT trial and a conventional trial, using real geographical data collected from Islamabad Pakistan. The results showed that the IoT-based system exhibited a considerably lower total travel distance and total travel time. However, there is still a gap in existing research regarding extending the system to multi-vehicle and multi-objective optimization, as well as testing robustness in larger datasets. Antora *et al*.[56] reported an IoT-enabled smart waste management system that employs sensor data and image-based machine learning algorithms to classify and segregate waste into multiple compartments, while enabling real-time monitoring through cloud connectivity. Juwariyah *et al*. [57] reported the design of an integrated monitoring system for multiple IoT-based smart bins in the context of waste management under the Industrial Revolution 4.0 paradigm. The proposed system utilized a Wemos D1 Mini Pro microcontroller in conjunction with an HC-SR04 ultrasonic sensor and a DHT22 temperature–humidity sensor to monitor waste fill levels and environmental conditions. An integrated real-time monitoring platform was developed using the Blynk application and Arduino IDE, enabling visualization of garbage height, temperature, and humidity data on smartphones through virtual indicators and graphical displays. Experimental evaluation was conducted using two smart bin units, demonstrating the feasibility of centralized real-time waste monitoring. Pebriad *et al*.[58] reported the design and development of an IoT-based Smart Waste Bin aimed at automated waste monitoring and management. The proposed system employed barcode sensors for waste type identification, an ESP32 microcontroller as the primary control unit, and an IoT cloud platform for real-time data visualization via a web-based dashboard. The study followed an engineering approach based on the waterfall model, encompassing requirement analysis, system design, implementation, and testing phases. Experimental results demonstrated a waste detection accuracy of 95% and an average data transmission delay of less than three seconds, indicating improved efficiency and responsiveness in waste management. The findings support the feasibility of smart, environmentally sustainable waste management systems. Abba *et al*.[59] presented an IoT-based smart garbage monitoring system employing an Arduino Uno microcontroller, ultrasonic sensors, and Wi-Fi communication to detect and classify bin fill levels as empty, half-filled, or filled. The system periodically displays bin status on an LCD and transmits real-time data to a centralized web server for graphical visualization. The prototype was developed using Arduino IDE with embedded C, while server-side data processing was implemented using PHP and simulated in Proteus 8.0. Experimental evaluations confirmed the system's effectiveness under real-world conditions, demonstrating its potential to support automated waste monitoring and smart city waste management.Jun-Ho Huh *et al*.[60] reported the limitations of the standard trash bag–based waste disposal system implemented in the Republic of Korea since 1995, particularly highlighting persistent issues of illegal dumping by households and businesses attempting to avoid disposal costs. Efforts by the Seoul Metropolitan Government to mitigate the problem by removing street trash bins proved ineffective, as illegal dumping continued to cause environmental, hygienic, and odor-related concerns. To address these challenges while reducing manpower and maintenance costs, the authors proposed an IoT-based smart trash separation bin model. The study presented three alternative system designs incorporating sensor-based detection, image processing, and spectroscope technologies, demonstrating the potential of IoT-enabled solutions to reduce labor requirements and administrative costs in urban waste management. Khan *et al*.[61] proposed a novel IoT-enabled, knapsack-based optimization framework for waste collection that leverages sensor data on waste quantity and toxicity to optimally load collection trucks while prioritizing high-toxicity waste. The model was implemented and evaluated using MATLAB simulations, where it outperformed conventional waste collection strategies. Experimental results demonstrated an improvement of up to 47% in high-priority toxic waste collection and a reduction in the number of collection trips, leading to equipment cost recovery within one year Lu *et al*.[62] introduces an ICT-based novel waste collection system that uses a hybrid bi-objective metaheuristic based OEGA, mixing a Whale Optimization Algorithm and Genetic Algorithm for balancing total cost and workload across multiple disposal centers. The proposed method was tested using real data from the Pudong community in Shanghai and the resulting multi-objective compound had better multi-objective optimization ability compared to the NSGA-II and MOEA/D. However, there was no implementation of a real-life case to substantiate the findings of this study. This demonstrates a gap in future research examining operational feasibility and cost of maintenance for the proposed waste collection system models. Aleyadeh *et al*.[63] proposed an IoT-based architecture that addresses two key components of smart waste management. The first component focuses on monitoring the waste volume and composition within bins, as well as environmental conditions in their surrounding areas. The second component enables dynamic scheduling and optimized routing of waste collection vehicles based on real-time data transmitted from the bins. The proposed smart bin design is capable of detecting obstacles and identifying illegal dumping activities in the vicinity. Furthermore, the routing protocol computes optimal collection paths for servicing filled bins in high-density residential areas while minimizing travel distance. The integration of these components enhances overall waste collection efficiency and contributes to a reduction in operational costs and carbon footprint.

3. AI/ML for prediction, classification & decision support

Namoun *et al*.[64] offers a thorough overview of machine learning (ML) applications in solid waste management for smart cities, specifically through optimizing waste flows organization. The authors reviewed 23 articles, which used artificial neural networks (ANNs) for predicting waste generation and waste disposal behaviors. The comparative approach, reviewing ML models and algorithms for waste forecasting was the method. Overall, the study results conclude that ANNs provide the most viable modelling processes for predicting trends in waste generation, due to its applicability to nonlinear patterns. Namoun *et al*. noted limited standardized and recently curated datasets for waste, as well as a lack of benchmark case studies, therefore highlighting a gap in research to support the development of robust and transferable models to explore datasets for comparisons. Alsabt *et al*.[65] explored the application of artificial intelligence (AI) and machine learning (ML) techniques to optimize waste management strategies with an emphasis on economic efficiency and environmental sustainability. Using the World Bank's comprehensive waste management dataset, the study conducted extensive data preprocessing, including cleaning and feature selection, to improve model performance. Several ML models, such as regression techniques, Support Vector Machines (SVM), Random Forest (RF), and Extreme Gradient Boosting (XGBoost), were employed to forecast waste generation trends and evaluate waste management alternatives. Additionally, optimization methods, including linear programming, were used to enhance resource allocation and operational efficiency. The proposed framework achieved an accuracy of 85 % in waste generation prediction, attributed to the incorporation of diverse socio-economic variables. Moreover, the optimization model resulted in a 15 % improvement in operational efficiency, demonstrating the potential of ML-driven approaches for sustainable and cost-effective waste management. Ali *et al*.[66] introduced an optimization framework that integrates machine learning and regression to improve economic and environmental performance in waste management systems. Synthetic datasets simulating the performance of different waste materials, and conversion technologies as configured and practiced in Malaysia were created to develop linear regression, multilayer perceptron (MLP), and sequential minimal optimization regression models. The authors identified the MLP as having the strongest correlation coefficient (0.7169), which was useful to predict the outputs of waste conversion. However, the authors did not validate the models against real-world, municipal waste data or analyze their generalizability, representing a notable research gap in using and testing this method in changing urban waste management processes.

Huang *et al*. [67] conducted a systematic review on the application of machine learning (ML) in the aerobic composting of organic solid waste (OSW). Although aerobic composting is widely used for producing organic fertilizers, its complex non-linear biochemical reactions and heterogeneous material properties limit accurate process simulation and optimization. The review examined ML-based approaches for predicting and controlling compost maturity, environmental pollutants, nutrients, moisture, heat loss, and microbial activity. The results showed that ML applications primarily focus on compost maturity and pollutant prediction, with artificial neural networks (47%) and genetic algorithms (10%) being the most commonly used techniques. Moreover, deep neural networks and ensemble learning models demonstrated enhanced predictive performance and effective feature selection, contributing to improved efficiency in organic waste composting. Boudanga *et al*.[68] offer an explainable artificial intelligence (XAI) framework for medical waste management. The framework consists of IoT sensors, GPS-enabled vehicles, and data analysis via AI model application, such as Decision Trees and Random Forests (RF) models to predict the fill level of medical waste and make routing decisions. The authors used experimental analysis of operational efficiency and resource optimization and collected data in real-world environments in Casablanca, Morocco. XAI enhanced interpretation of findings, but the researchers did not benchmark the frameworks performance with comparative model findings in existing literature. The research gap is in benchmarks for performance on explainable AI in medical waste management logistics with real-time expandability testing. Gupta *et al*.[69] reviewed a wide range of data-driven modeling techniques for organic waste treatment technologies, highlighting their potential contribution toward achieving net-zero targets. The study discussed advanced machine learning (ML) methods, including neural networks (NN), physics-informed neural networks (PINN), support vector machines (SVM), decision trees (DT), random forests (RF), XGBoost, k-nearest neighbors (KNN), and Gaussian process regression (GPR), applied to the modeling, optimization, and control of both high- and low-temperature waste treatment processes. Emphasis was placed on model explainability techniques to interpret black-box ML models and enhance transparency. The integration of ML with physical governing laws through PINNs was identified as a promising approach to improving model reliability and robustness. Additionally, the study highlighted the importance of combining ML models with control algorithms, heuristic optimization methods, life cycle assessment frameworks, and natural language processing techniques to support holistic and circular organic waste management strategies

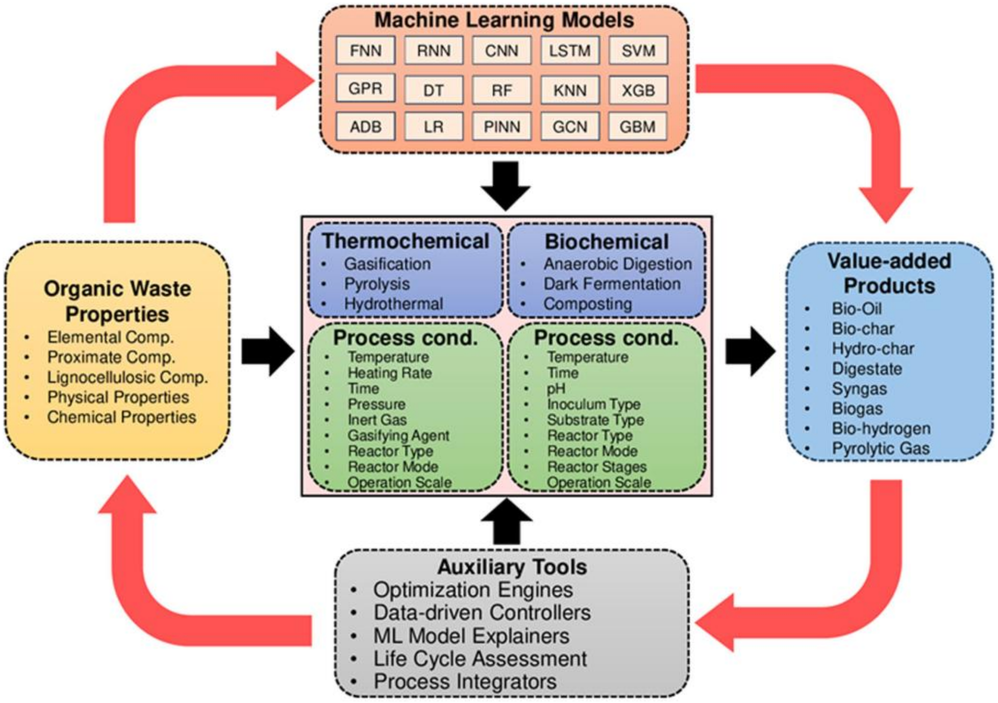

Fig. 3: Overview of thermochemical and biochemical organic waste treatment technologies. Reproduced from [69].

3. Circular Economy, Policy, Citizen Engagement & Systems Integration

The circular economy (CE) is currently an integral part of sustainability. Bandh *et al*.[70] examined the interrelationship between waste management and the circular economy as complementary frameworks for achieving environmental sustainability. The study emphasized that effective waste management-through recycling, reuse, and proper disposal-plays a critical role in minimizing environmental risks and reducing waste generation. Within a circular economy, principles such as designing out waste and pollution, maintaining materials in continuous use, and regenerating natural systems enable the development of closed-loop systems that convert waste into valuable resources. The authors highlighted the importance of the three core principles of the circular economy-reduce, reuse, and recycle-in lowering environmental impact, conserving resources, and supporting eco-friendly industries. Overall, the study underscored that integrating waste management practices within circular economy models can promote sustainable development while delivering environmental, economic, and social benefits. Mridu Kulwant *et al*.[71] examined the role of waste management within the framework of a circular economy, contrasting it with the traditional linear “take–make–dispose” economic model and its associated environmental challenges. The chapter highlighted the growing shift toward circular economy principles that emphasize resource efficiency, waste reduction, and sustainable consumption patterns. Key strategies and principles were discussed, focusing on waste minimization and value creation through sustainable practices. The authors also reviewed innovative technologies and approaches that are transforming waste management systems and facilitating the transition to circular models. Through real-world examples and case studies, the chapter demonstrated how circular economy adoption can reduce environmental impacts and support the development of a sustainable and resilient future. Rashmi Paliwal *et al*.[72] discussed the escalating pressure on natural resources caused by industrialization and population growth, which has resulted in increased waste generation and environmental contamination. The study contrasted natural ecosystem cycling, where waste does not exist, with anthropogenic linear economic models that introduce waste through “take–make–dispose” practices. Highlighting World Bank projections of a nearly 70 % increase in global waste generation by 2050 if unmanaged, the authors emphasized the urgency of adopting alternative models. The chapter positioned the circular economy as a transformative approach for sustainable production and consumption, enabling recycling and the creation of “wealth from waste” through strategies such as the 3R principles, eco-design, and energy-efficient products. Additionally, it examined the challenges associated with multiple material cycles and downcycling, offering insights into achieving a zero-waste economy. Salman Shooshtarian *et al*.[73] examined the role of circular economy (CE) principles in improving construction and demolition (C&D) waste management within the built environment sector. The chapter emphasized that enforcement, alongside encouragement and education, plays a critical role in advancing resource circularity through effective policy interventions. Eight key policy measures-such as landfill taxation, penalties for illegal dumping, extended producer responsibility, sustainable procurement, and recycled product certification-were analyzed for their impact on waste recovery and resource efficiency. Using

Australia as a case study, the authors combined literature and policy analysis with stakeholder surveys and interviews conducted between 2018 and 2021. The findings provide both conceptual and practical insights to support the development of evidence-based waste management policies aimed at enhancing circularity in the built environment. Josephine Treacy *et al*.[74] examined the role of waste management policy and stakeholder engagement in achieving the United Nations Sustainable Development Goals (SDGs). The chapter emphasized that effective policy implementation, supported by strong engagement across civil society and institutional stakeholders, is essential for embedding the SDGs into national and regional strategies. Focusing on solid and liquid waste management, the study analyzed challenges related to water quality, sanitation, air quality, and soil degradation arising from weak policy execution and limited stakeholder involvement. From a European perspective, with particular emphasis on Ireland, the authors identified best practices, implementation gaps, and consequences of ineffective waste management policies. The chapter highlighted SDG 17 as a critical enabler, underscoring the importance of integrated bottom-up and top-down communication approaches for achieving sustainable waste management and public health outcomes. Hashim Zameer *et al*.[75] explored the role of environmental economics in shaping effective waste management policies by examining the social costs associated with waste generation, including pollution, health risks, and resource scarcity. Using a content analysis approach, the study developed a theoretical framework emphasizing the "polluter pays" principle to encourage waste reduction and sustainable production practices. The authors highlighted the use of fiscal policy instruments such as taxes, fines, subsidies, landfill taxes, and pay-as-you-throw schemes as effective economic incentives for reducing waste and promoting recycling. Additionally, the study emphasized the importance of developing recycling markets through waste-to-energy initiatives, deposit-refund systems, and support for recycling enterprises. Overall, the chapter demonstrated how environmental economics can guide policy design to reduce waste disposal, stimulate economic activity, and conserve natural resources. Berger *et al*.[76] developed an economic model of packaging waste management to examine government policy options under the framework of Extended Producer Responsibility (EPR). The model explicitly incorporated packaging design, consumer sorting behavior, and producers' output decisions as joint determinants of total waste generation. The findings revealed that policies achieving first-best outcomes may lack public acceptability and that constrained policy instruments can lead to sub-optimal production and consumption levels, even when optimal allocations are theoretically attainable. Moreover, the study showed that landfill taxation may unintentionally increase landfill waste when combined with tradable recycling credits. These results highlight critical limitations in existing regulatory schemes, including the UK's Producer Responsibility Obligations for packaging waste.

Chikkahanumaiah *et al*.[77] examined citizen engagement strategies and waste management challenges in Varamballi Gram Panchayat, located in Brahmavara Taluk of Udupi district. The study identified key issues, including low public awareness, weak Panchayat administration, and unscientific and illegal waste disposal practices. These challenges were largely attributed to population growth and rapid development activities such as real estate expansion, small-scale industries, and the growth of commercial establishments. Using qualitative research methods, data were collected through unstructured, in-depth interviews with ten adult respondents. Interpretive phenomenological analysis (IPA) was employed to analyze the findings, providing insights into community-level waste management dynamics and engagement barriers. Tembo *et al*.[78] addressed growing waste management challenges in urban areas by proposing a comprehensive, citizen-centered waste management system implemented through a user-friendly web application. The platform enables residents to report, track, and provide feedback on waste-related issues, supported by geolocation services to improve reporting accuracy. Municipal authorities can respond to reported issues and update their status, thereby enhancing transparency and accountability. Data security is ensured through the use of hashing algorithms such as Bcrypt to protect user information. The proposed system aligns with Sustainable Development Goals SDG 11 and SDG 12, promoting sustainable urban development through improved resource efficiency and waste reduction. Mishra *et al*.[79] investigated the role of machine learning in enhancing public participation and environmental awareness to support sustainable waste management. The study evaluated classification models, including logistic regression, random forest, k-nearest neighbors (KNN), and decision trees, using waste composition and treatment datasets. Model performance was assessed through multiple metrics, such as accuracy, precision, recall, and F1-score. The Random Forest model achieved the best performance, with 89 % accuracy and an F1-score of 86 %, demonstrating strong capability in forecasting citizen engagement behavior, while decision tree models also showed promising potential. The findings highlight how ML-driven civic engagement strategies can improve recycling rates, reduce open dumping, and enable collaborative waste management planning between governments and local communities.

4. Research gaps

Despite significant advances in smart waste management, IoT integration, and robotic automation, most of the studies indicates that the development of fully autonomous, intelligent, and adaptable robotic systems for waste collection and sorting in public environments remains an emerging and underexplored research area. Most existing studies primarily focus on smart bin designs, IoT-based monitoring systems, and data-driven route optimization.[80] Consequently, there is a notable lack of fully integrated systems capable of autonomously managing the entire waste handling process, including waste detection, collection, classification, and final disposal. A key limitation identified across the reviewed studies is the insufficient integration of artificial intelligence (AI), robotics, and IoT into a unified framework. While several works incorporate IoT-enabled smart bins for monitoring and alerting, they often rely on human-operated vehicles for physical waste collection.[54,56,57] Conversely, robotic arms and mobile platforms-largely evaluated in laboratory or controlled environments may support autonomous collection and sorting but frequently lack IoT-based communication and system-level coordination.[20,21,40] This separation between cyber (IoT) and physical (robotic) components restricts scalability and coordinated operation across large public spaces. Waste classification represents another critical research gap. Many current systems depend on basic sensor-based segregation using moisture or inductive sensors, limiting classification to coarse categories such as dry, wet, or metallic waste. Although vision-based approaches using deep learning techniques (e.g., CNNs and YOLO) have shown promising results in controlled environments, their robustness in real-world outdoor settings remains limited due to challenges such as variable lighting, occlusion, and irregular waste shapes.[23,33] This highlights the need for robust, sensor-fused AI models capable of reliable real-time waste classification in dynamic environments. Furthermore, the majority of reviewed systems operate within simulated or semi-controlled settings, constraining their applicability to real-world scenarios. Limited attention has been given to practical deployment challenges, including dynamic obstacle avoidance, uneven terrain, battery constraints, and changing weather conditions. Autonomous navigation, energy efficiency, and adaptive decision-making under uncertain outdoor conditions remain insufficiently addressed in existing research.

Finally, the communication and fleet management aspects of autonomous waste collection robots are relatively under-researched. Few studies explore multi-robot coordination, cloud synchronization, real-time analytics, or predictive maintenance. Emerging technologies such as edge computing, low-power IoT protocols, and 5G connectivity offer significant potential to improve scalability, reliability, and operational efficiency, yet remain largely unexplored in this domain. Future research should focus on developing holistic AI–IoT–robotics frameworks for autonomous waste management, robust vision-assisted classification systems for outdoor environments, energy-efficient and adaptive navigation strategies, and scalable multi-robot coordination architectures to support sustainable smart city waste management.

4. Discussion

The survey of current research on intelligent waste management systems reveals a rapidly evolving yet fragmented research landscape. While there is broad consensus that future waste management solutions will increasingly integrate robotics, the Internet of Things (IoT), and artificial intelligence (AI), most existing studies address these components in isolation.[50,58,65,66] The integration of these technologies into a seamless and fully autonomous system remains a significant challenge for both researchers and practitioners. This section discusses key insights, comparisons, and technological implications derived from the reviewed literature, particularly in the context of comprehensive robotic waste management systems. One major finding is that the majority of existing systems emphasize monitoring rather than physical action. IoT-based waste management solutions primarily rely on smart bins equipped with sensors, GSM modules,[37] and cloud dashboards to monitor fill levels and notify authorities. Although such systems improve awareness and scheduling efficiency, they continue to depend on human-operated vehicles for waste collection. In contrast, robotic systems such as autonomous sweepers or manipulators focus on physical waste collection but often lack real-time data connectivity and centralized monitoring. This separation highlights the need to integrate IoT-enabled data intelligence with robotic actuation to enable truly autonomous waste collection.

Another critical issue concerns the autonomy and adaptability of existing systems. Most reported prototypes operate in structured or semi-structured environments, such as indoor facilities or controlled testbeds. However, real-world public environments are highly unstructured and dynamic, characterized by pedestrian movement, uneven terrain, weather variability, and irregular waste distribution. Current systems based on ultrasonic or infrared sensing exhibit limited adaptability under such conditions. Emerging approaches, including LiDAR-based mapping, stereo vision, and deep reinforcement learning for adaptive navigation, demonstrate strong potential but remain underexplored in waste management applications. Future systems must evolve beyond preprogrammed routes toward adaptive, learning-based navigation strategies. From an AI perspective, waste classification and segregation remains a complex yet impactful challenge. Basic sensor-based methods using inductive or moisture sensors enable only coarse classification into categories such as metallic, dry, or wet waste. Although computer vision and convolutional neural networks (CNNs) have achieved high accuracy in laboratory settings for identifying recyclable materials, their deployment on outdoor mobile robots is constrained by computational requirements, energy consumption, and environmental variability. Lightweight deep learning models (e.g., MobileNet, Tiny-YOLO) combined with edge computing platforms offer promising directions for achieving efficient and robust real-time classification in field conditions.[23]

System sustainability and energy efficiency also emerge as critical considerations. Most robotic platforms rely on battery-powered motors without advanced power optimization strategies, limiting operational duration in large public spaces.[41] Integrating solar-assisted charging, low-power microcontrollers, and intelligent power management algorithms could significantly enhance system autonomy. Additionally, the deployment of autonomous docking or wireless charging stations within urban infrastructure could enable continuous, unattended operation, supporting long-term sustainability goals. The communication and data management architecture further influences system scalability. While GSM and Wi-Fi are commonly used, they may suffer from latency and reliability issues in open urban environments. Alternative communication technologies such as LoRaWAN, NB-IoT, and 5G offer improved range, reliability, and energy efficiency. Hybrid data architectures that combine local edge processing with cloud-based analytics can support both real-time responsiveness and long-term optimization, enabling large-scale institutional deployment. Finally, multi-robot collaboration represents a promising yet underexplored research direction. Most current systems operate as standalone units within limited areas. Coordinated fleets of autonomous waste robots, managed through centralized IoT platforms, could dynamically allocate cleaning tasks based on real-time waste density and geographic data. Techniques such as swarm intelligence and multi-agent reinforcement learning (MARL) may enable efficient cooperation, route negotiation, and resource optimization across large urban environments.

5. WasteXpert Auto: a conceptual advanced and integrated waste management system

The WasteXpert Auto is advanced and integrated waste management system fill these gaps by creating a fully autonomous waste collection robot capable of operating autonomously and safely in public environments. The WasteXpert Auto system includes several integrated modules: a perception module for detecting waste or obstacles, a navigation module for the robot to autonomously navigate the space, a manipulator to collect the waste, a sorting module to sort the waste, and a communication system that transmits this data on-demand. The perception module uses ultrasonic and infrared sensors to obtain distance measurements, a vision camera to detect objects, and additional sensors to measure the presence of water, and humans in the environment to ensure safe operation. The navigation module relies on GPS, IMU, and encoder data for accurate localization and efficient path planning. The robot arm mechanically collects waste it detects and places it into a dedicated internal sorting unit that automatically categorizes the waste as dry, wet, or metallic with inductive and moisture sensors. This on-board sorting process will reduce the need for manual segregation of waste further on in the recycling process, thereby improving the overall recycling efficiency. Once the internal bins are full, the robot will navigate to the closest dustbin or waste disposal point, recognized through a combination of GPS data and IoT-based mapping, and will deposit its waste back into the dustbin before returning to its designated area to continue operation.

The communication system based on Internet of Things (IoT) is the most important part of WasteXpert Auto. The robot is then able to send telemetry data which include the hotels of the bin, battery life, and location back to either the cloud server or from an Android application interface using any of the protocols either the GSM or MQTT. The municipalities or operators using the interface can monitor multiple robots at that time, schedule servicing of their robots in house and notified of emergency situations for example low battery or bin overflows. The Android application has a feature a human operator can take manual control to start, stop, or re-route the robot as required. A communication system of this nature easily aligns with the objectives of smart city initiatives such as the Swachh Abhiyan initiative in India, which utilizes technology to promote cleanliness and sustainability. The use of automation in waste management is not only about increasing operational efficiency; it has many indirect potential benefits for public health, environmental protection, and urban sustainability. Automation here could facilitate less human exposure to waste and, therefore, reduce the risk of a disease propagating, while also enhancing a city's visual feel. Intelligent sorting at the source could improve recycling rates, decrease landfill needs, and protect our resources. It is not unreasonable to see that in the future this may be extended to robots interfacing with a centralized IoT platform to form a smart waste ecosystem, allowing for coordination and data sharing from multiple robots and smart bins to streamline routes for increased efficiency, and predict and classify waste generation while allocating resources dynamically.

There are multiple facets of the engineering profession because of the interdisciplinary characteristic of having a robot that can autonomously manage waste. This can be accomplished by integrating robotics, embedded systems, artificial intelligence algorithms, power management, and environmental sensing. For example, a robot that has to navigate through an outdoor public space should be able to avoid obstacles, conserve power, and respond to dynamic conditions such as pedestrians and uneven surfaces. When developing a manipulator to remove waste, the designer has to consider the manipulator has to meet more degrees of freedom and accuracy when it is manipulating irregularly shaped objects. The waste classification task will require the robot to correctly calibrate sensors and process the information in real-time. The communications module will need to remain connected in areas with low signal so that communications can remain ongoing. All of these components just to name a few will contribute to the overall performance and reliability of the system. In the case of WasteXpert Auto, the primary contribution of the proposed system is that it combines full autonomy and advanced intelligence from a sorting and IoT-based monitoring platform in a single system. It not only automates waste collection, but incorporates decision-making, communications, and safety and has been designed to operate continuously in public spaces. It is modular as well, meaning further developments will offer continuous scalability (across vast zones, multiple robots can combine their operation, all monitored through a central platform). These developments will be a monumental development toward cleaner, safer, more intelligent cities. The growing complexity of urban waste management necessitates a transition from conventional manual practices to intelligent, automated, and sustainable solutions. This review analyzed 37 representative studies addressing smart waste management through IoT-based monitoring, machine learning-driven prediction, route optimization, and robotic automation. The analysis reveals that, although significant progress has been made in individual subsystems, most existing efforts remain fragmented and do not yet realize fully autonomous, end-to-end waste management systems. The review highlights that current solutions largely focus on isolated components such as smart bins, sensor-based monitoring, or optimization algorithms, while comprehensive integration of artificial intelligence, robotics, and IoT within a unified operational framework remains limited. Challenges related to scalability, energy efficiency, environmental adaptability, and multi-robot coordination continue to restrict real-world deployment in dynamic public environments. Despite notable advancements in sensing technologies, navigation strategies, and machine learning models, further research is required to address system-level integration, energy-aware operation, robustness in outdoor environments, and coordinated fleet management. Future research should prioritize unified AI–IoT–robotic architectures, edge-enabled intelligence, renewable energy integration, and collaborative robotic systems to enable scalable and sustainable urban waste management. Within this context, the conceptual framework of WasteXpert Auto is positioned as a representative direction toward next-generation autonomous waste management. By integrating real-time sensing, autonomous navigation, intelligent waste classification, and IoT-enabled monitoring, such systems demonstrate the potential to reduce human intervention, improve operational safety, enhance recycling efficiency, and support smart city objectives. Overall, this review provides a structured understanding of the current research landscape, identifies critical gaps, and outlines future directions that can accelerate the development of fully autonomous, intelligent, and sustainable waste management systems for smarter cities.

6. Conclusion

The increasing complexity of urban waste management demands a decisive transition from conventional manual practices toward intelligent, automated, and sustainable solutions. This review critically examined 37 representative studies addressing smart waste management through IoT-based monitoring, machine learning–driven prediction, route optimization, and robotic automation. The analysis indicates that, while notable progress has been achieved across individual subsystems, most existing approaches remain fragmented and fall short of delivering fully autonomous, end-to-end waste management solutions. The findings reveal that current research predominantly emphasizes isolated components—such as smart bins, sensor-based monitoring, or optimization algorithms—rather than holistic system integration. Limited coordination between artificial intelligence, robotics, and IoT frameworks continues to constrain real-world deployment, particularly in dynamic and unstructured urban environments. Persistent challenges related to scalability, energy efficiency, terrain adaptability, robustness, and multi-robot coordination further hinder large-scale adoption. Within this context, the conceptual framework of WasteXpert Auto represents a promising direction for next-generation autonomous waste management systems. By integrating real-time sensing, autonomous navigation, intelligent waste classification, and IoT-enabled monitoring within a unified architecture, such systems highlight the potential to reduce human intervention, enhance operational safety, improve waste segregation efficiency, and align with smart city sustainability objectives. Despite advances in sensing technologies, navigation strategies, and machine learning models, further research is required to address system-level integration, energy-aware operation, resilience in outdoor environments, and coordinated fleet management. Future work should prioritize unified AI–IoT–robotic architectures, edge-enabled intelligence, renewable energy integration, and collaborative multi-robot systems to enable scalable and sustainable urban waste management. Overall, this review provides a structured understanding of the current research landscape, identifies critical gaps, and outlines clear future directions that can accelerate the development of fully autonomous, intelligent, and sustainable waste management systems for smarter cities.

Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable

Use of artificial intelligence (AI)-assisted technology for manuscript preparation

The authors confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the

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