

WasteXpert Auto: A Review of Robotic and IoT Technologies for Automated Waste Handling

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Abstract: According to the abstract, urbanization and population growth have made waste management more challenging in urban areas (parks, streets/public transport). The traditional method of waste collection requires significant manual labor and is inefficient, expensive, and poses numerous health hazards to sanitation workers. Recently, robots, artificial intelligence (AI), and the Internet of Things (IoT) have developed autonomous, human-activated, intelligent waste management systems that can detect, collect, and separate waste. This paper reviews the intelligent robotic solutions to automated waste collection and separation. Several subsystems of intelligent robots will be discussed: perception, navigation, manipulation, sorting, and IoT, the last of which is also known to produce waste management data. Other sensors technologies will be described including ultrasonic sensor, inductive sensor, and moisture sensor in addition to machine vision and deep learning algorithms for waste proper classification. The use of communication architectures will also describe how robots use gsm, gps, or a mobile app while talking to a user in real-time to track and operate the robot. There will also be a discussion, using examples, detailing the automated systems to date, and while many advances have been made towards automation in waste collection there are still many long-term challenges, particularly around energy, outdoor usage, or the implementation of systems to work on a wide scale.

Keywords: Autonomous Waste Management, Intelligent Robots, WasteXpert Auto, Smart City, Internet of Things (IoT), Artificial Intelligence (AI), Waste Segregation, Robotic Waste Collection, Environmental Sustainability, Machine Vision

I. INTRODUCTION

The management and disposal of solid waste can be considered one of environmental as well as operational crises in contemporary cities. Changes associated with rapid industrialization, urbanization, and increased population sizes have led to unprecedented amounts of solid waste generated daily in public space. 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 methodologies for collection and disposal are labor-intensive and follow regular (or non-regular) cleaning schedules that are largely ineffective, inefficient, and inconsistent. 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. Waste collection becomes evident when bins overflow, litter expands outward from the bin, or solid waste is left lying around after a human trafficking event. Solid waste all around is not only aesthetically displeasing to the public but also has significant negative ecological and health impacts that can result from the generation of infectious diseases, clogged/blocked drainage systems, contaminated soil and water resources, etc. 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.

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 possible that can perform complicated tasks autonomously. 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. The use of robots with autonomous technology in waste management is relatively new but swiftly advancing. 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. Autonomous waste-collecting robots will be excellent for public spaces where catastrophic waste generation can occur that is always needing to be cleaned and there can be no disruption in cleanliness. An example of an autonomous waste-collecting robot is WasteXpert Auto as 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.

There are many limitations that exist with existing waste management systems. Manually collecting waste is laborious, inefficient, and oftentimes unsafe. Waste collectors are often exposed to dangerous materials, sharp objects, and pathogens with no protective gear, leading to significant hazards to health. 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. 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. 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. 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. 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. 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. Early systems primarily designed for mobile waste collection in urban streets include DustCart developed in Europe, 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. 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.

The WasteXpert Auto project seeks to 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 details 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 SwachhAbhiyan 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.

Although remarkable progress has been made, there are still hurdles to deploying fully autonomous waste collection robots at a scalable level. Power management remains a substantial limitation, particularly with regard to employing energy efficient power systems and possibly renewable power sources like solar charging. Terrain adaptability is also a challenge, since most robots are optimized for flat surfaces and typical environmental situations may have slopes, curbs, or wet areas. Maintenance, cost, and durability of parts will also hinder minimum return on investment for large-scale adoption. Nevertheless, research addressing lightweight materials, motor control and artificial intelligence will carefully proceed and eventually overcome these concerns.

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 introduction of autonomous robotic systems into waste management is shifting from manual, labor intensive tasks, to smart, automated, and data-driven environmental improvement technologies. This review has assessed the technological foundations, deployments and research paradigms in robotic waste management and assesses the



integration of the separate approaches to machine perception, navigation, waste sorting systems and communication intertwine each other. Finally, it contextualizes WasteXpert Auto as an example of a fully integrated autonomous system that can address real-world operational issues related to waste collection. This review of advancements will position the state of robotic waste management, gaps in current research and note areas for further research and its applications to sustainable urban sanitation.

II. LITERATURE SURVEY

Review & Taxonomy Studies

Nižetić et al. [1] 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.

Pardini et al. [2] 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.

An analysis of IoT technologies indicated to small-city WMS is presented by Rasool et al. [3]. The authors had completed a descriptive review of 18 studies that summarized the technological foundation and software used to monitor waste data. The authors found a basic application of IoT in urban small-scale contexts, but they did not provide systematic comparisons nor describe challenges. The gap in the research stems from having a lack of depth and missing technologies in small developments. Sodiq et al. [4] provides a review of food waste management in smart cities regarding technology and environmental implications of waste disposal practices. Using qualitative analysis, only one group of authors discussed a dual use of food waste disposers which reduce volumes in landfills yet could damage sewer systems. The study reviewed that food waste represent 50-55% of solid waste in developing countries. The key gap of the research was there was no long-term evaluation of their environmental trade-offs in such technologies.

Sahu et al. [5] provide a review of 15 studies on the use of emerging industrial technologies to facilitate waste sorting in urban systems in India. The authors reviewed the literature using content analysis for the examination of scientific articles and technical reports. The study documented many significant technological innovations in waste sorting, although territory was limited to Indian metropolitan areas. Sahu et al. [5] found a justifiable limitation in that the literature review had a limited geographical focus without ability for cross-country comparison. Ahmad et al. [6] undertook a systematic review of the role of blockchain in waste management systems (WMS). The authors examined if blockchain could improve real-time tracking and tracing of waste and verify compliance through smart contracts. While the authors found that blockchain could enhance reliability and transparency in the continuously complicated and inconsistent collection, separation, recycling, and removals offerings of waste management, they identify a gap in research with scaling and empirical validation of a blockchain-enabled WMS in real-world use.

Akram et al. [7] 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.

Ramirez et al. (2018) 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. (2020) 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. [10] 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. Mousavi et al. [11] provides a review of IoT-based waste management systems, discussing the data acquisition, data processing, and spatial processing technologies including GIS, GPS and remote sensing. The study mapped the flows of data from various IoT and integration with spatial systems in order to advance logistics and monitoring. However, in comments about the study limitations, the authors discussed a lack of full dataset standards and benchmarks.

Namoun and colleagues [12] conducted a review of machine learning (ML) approaches in organizing waste collection and modelling waste disposal behaviours. The authors reviewed 23 publications and disclosed artificial neural networks (ANNs) as the most common ML algorithm used for predictive studies. The results indicated that ML can be used to model waste generation patterns, however, a lack of benchmark datasets posed challenges for comparative analysis. The authors identified a research gap with the lack of open-access datasets and recent data that can support ML-based WMS models. Sosunova and Porras [13] provided a review of 173 studies reviewing IoT applications in urban waste management systems (WMS) from 2014 to 2022, along with a structured taxonomy of studies. Their taxonomy categorised studies into two main themes: city-based WMS (consisting of routing, optimization, and impact) and smart-bin technologies (focusing on sensing and communication). The review summarized how IoT data can support decision-making, reduce costs, and lessen environmental impact with the gap in research being limited use of IoT for predictive analytics and large scale optimization.

In their review, Vishnu et al. [14] examine sensor technologies that integrate with WMS, including RFID, wireless sensor networks (WSNs), and IoT-enabled sensors during the period between 2007 and 2021. The authors found that IoT-based sensors have greater flexibility and interoperability than conventional technologies and identified LoRaWAN as the most suitable communication protocol. The gap is the base of evidence comparing field testing of multiple sensor technologies across different environmental and infrastructure contexts. Fang et al. [15] conducted a review of computational intelligence in WMS. This review organized its findings into nine thematic sections; the use of AI can be examined within smart bins, sorting robots, and logistics. The findings indicated that the use of AI has the potential to increase efficiency and sustainability. The research gap is that currently, there are no empirical studies to evaluate socio-economic and ecological consequences of AI in WMS.

IoT Architectures & Smart-Bin Designs

Monishan et al. [16] examine an IoT-based solution to optimize waste collection and disposal to reduce cost through effective routing. Their design involved using bins located at households along with automated mobile waste collectors and routing algorithm to calculate the shortest path to collect waste around the the collection points. Experimental validation occurred in a synthetic test-bed environment. Here, it was noted that the provided routing improved organization and distance traveled during collection in simulated environments. An identified gap in the promoted work is that it is unknown if the methodology has been validated in real urban conditions and against existing routing algorithms.

A waste management system based on IoT technology was proposed by Idwan et al. [17] 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.

Ahmad et al. [18] propose a recommendation-based optimization system aimed at reducing the distance of collection routes and the cost associated with fuel consumption while maximizing the volume of waste collection. The authors framed the problem in a way that considers constraints with a mixed-integer linear optimization model to optimize the waste collection system. They solved the model using Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Bat Algorithm. They used real data on waste in Jeju Island, South Korea, from 2017-2018 to evaluate the methods. When comparing the methods on the basis of cost and fuel retuning efficiency of the waste collection, they found that PSO performed best. The authors note a gap in the literature in that the system methodology has not been implemented within a real-world application, nor has a methodology that can dynamically adjust to changing demand in regards to waste generation pattern.

Hannan et al. [19] provide a routing optimization model that uses real-time status information of the bins to achieve increased efficiency in waste collection and reduced emissions. Although the proposed system utilized fixed and variable routing models, the modeling approach was tested on a fictitious scenario involving one depot, two vehicles, and twenty randomly distributed bins on an Euclidean plane. The results established the ability of the optimized routing models to significantly reduce costs associated with waste collection and provided an effective schedule. However, the primary research gap remains in the utilization of a small-scale synthetically generated environment with no real-world or validation of the routing models in the context of complex logistics networks related to waste management systems.

Nidhya et al. [20] studied a new routing algorithm for smart waste management systems, while investigating Quality of Service (QoS). Their research implemented an Enhanced Route Selection (ERS) algorithm to reduce data communication delay, while enabling routing from bins to dumps yards. The researchers tested performance using an NS-3 simulator. The researchers found that ERS routing could reduce latency, and provide enhanced throughput compared to traditional routing algorithms. However, there exists a research gap for an implementation and tests of communication efficiency in a real-world research design while accounting for variable network loads.

Nowakowski et al. [21] proposed a model for vehicle routing of e-waste through a metaheuristic. The researchers defined their model within the context of a Vehicle Routing Problem (VRP). This study used a Harmony Search algorithm in developing a solution method to identify optimal routes for waste collection within a period of time available. The authors assessed performance against randomly generated problem instances base on real-world circumstances. The Harmony Search technique was determined to be most efficient compared with Tabu Search and Simulated Annealing. Nevertheless, no type of implementation or field data validation was explored, thus identifying a distinct gap in the literature regarding the performance and scalability of an algorithmic approach with real-world operational constraints.

Wu et al. [22] develops a hybrid optimization model for wet waste collection and transport as a constrained capacitated VRP with carbon emissions and credible levels costs. The authors use a combination of PSO and Simulated Annealing techniques, with the goal of minimizing total operational costs. The authors also tested the heuristics on ten benchmark datasets and achieved superior performance across many scenarios. The research gap is still the lack of validating routing in real-time dynamic situations and merging IoT sensor data to establish adaptive routes.

Abdullah et al. [23] introduce a mixed GA Dijkstra metaheuristic that seeks to optimize routing in wireless sensor networks and ad hoc network setups for IoT-enabled waste management. The approach successfully identified effective, and alternative communication paths, while also minimizing distance and communication/data costs. Simulation experiments conducted in different network setups found evidence of path delays being improved and resistance to failure. The only limitation in the study is the lack of a physical system implementation which was a gap in evaluating the performance of the network resilience to urban signal interference and hardware constraints.

Lu et al. [24] 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.

Kshirsagar et al. [25] present a real-time shortest path routing algorithm for waste collection, which draws on the input from Internet of Things (IoT) sensors that exist in the field environment. Generally, the routing model was coupled with fill-level data and inter-bin distance, as well as performance measures that included packet size and end-to-end delay. The simulations showed that the algorithm generated a superior overall revenue for waste collection efforts. However, a research gap is that there are no field trials or dynamic performance testing with load variation.

Ali et al. [26] have developed a data-centric optimization framework with machine learning regression models for joint economic and environmental optimization. Three different types of regression were applied—linear regression, multilayer perceptron, and sequential minimal optimization regression—using synthetic datasets from a specific region of Malaysia. The multilayer perceptron model was shown to have the highest correlation coefficient of 0.7169, and therefore demonstrated its predictive capability. The key research gap continues to be a lack of model generalization and model validation with real-time operational data.

Akbarpour et al. [27] introduce a hybrid metaheuristic framework that incorporates Geographic Information Systems (GIS), Simulated Annealing (SA), and Particle Swarm Optimization (PSO) algorithms to minimize transportation costs and maximize recycling revenue in a waste management system. Using 10 industrial case studies, the researchers found the hybrid GA-PSO yielded the most cost-effective routes. Parameter robustness was further supported by the sensitivity analysis. However, the authors' approach was only implemented within a controlled environment, and the performance and scalability were not fully investigated within a live waste management system scenario.

Bin et al. [28] describe a variation of the Ant Colony Optimization (ACO) algorithm with non-dominated sorting to solve a split-delivery Vehicle routing problem (VRP) for scheduling waste collection. Modeling included cleaning for multiple services at the same place and the case study was in Tianjin Wudadao, China, with 32 waste collection points, and four disposal stations. While the variations of ACO improved vehicle use and total costs relative to use of traditional ACO, a real-world testing case study does support further research for waste collection algorithms while part of improvement is needed for algorithm performance under uncertain rates of waste generation.

Manoharam et al. [29] developed an optimization method for waste collection routes through the Tabu Search and Dijkstra algorithms on the ArcMap/ESRI platform. Although validated - the applicability of the GIS model was for 24 companies located at an industrial park in Malaysia, and reduced operational costs and transportation distances. However, the study does not compare alternative metaheuristics indicating a need for enhancement in benchmarking for route optimization alternatives.

Mekamcha et al. [30] also developed a hybrid Tabu Search and Simulated Annealing algorithm for optimizing waste collection routes in City of Tlemcen, Algeria. A real dataset was using analysis of 21 circuits. The Simulated Annealing method produced smaller total distances compared to the Tabu Search method, but the lack of implementation and validation of the work in real-life municipal operations leave a gap in valid assessment of practicality.

AI/ML for Prediction, Classification & Decision Support

Namoun et al. [13] 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. [13] 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.



Ali et al. [26] 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.

Soo and colleagues [31] provide a literature review of machine learning methods to improve composting of organic waste, with particular focus on emission prediction and monitoring of composting processes. The execution involved analyzing research literature on the use of machine learning models for logistics management and waste sorting. Results of the study indicate that predictive analysis from machine learning could improve composting efficiency and waste reduction in both time and space. However, other disadvantages of studying machine learning are limited dataset size and a lack of generalizability. The gap in research is developing robust machine learning models to learn from small datasets, as well as utilizing fog and edge computing for real-time composting efficiency improvement.

Boudanga and collaborators [32] 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 framework's 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.

Pollak et al. [33] propose an AI-assisted robotic waste collection system which includes predictive analytics and autonomous route planning capabilities of the robotic arm. This system used a greedy algorithm for optimal route calculation, in combination with XGBoost for bin-fill level predictive analytics. The evaluation was based on simulation experiments using synthetic datasets created from a real-world case study in Berlin, focusing on energy consumption and route efficiency. While the architecture and resulting simulation showed promise for the efficacy of their scenario-based study, there remains a research gap in terms of validating this aspect of the system in situ and under a continuous assessment to determine long-term use in situ in varied environmental and traffic conditions.

John et al. [34] presented a waste disposal prediction system which integrated the use of the Internet of Things (IoT) and their WASTECYCLE, based on long short-term memory (LSTM) networks. The system included sensors—ultraviolet, and weight sensors—to capture 'real-time' data on bin-level, and used Wi-Fi to transmit that data to the central processing server. The LSTM-based algorithm was used to predict the accumulation of waste 15 minutes ahead, with stacked LSTM variant yielding the highest level of accuracy. However, this study only provided evaluation based on 160 data samples collected over a 3-day time frame, limiting the generalizability of these findings. The gap in research can be conceptualized as a need for larger, longer yet continuous datasets and additionally, evaluations based in deployment that allow for validation data on the reliability of forecasting in real-world contexts.

Circular Economy, Policy, Citizen Engagement & Systems Integration

Nižetić et al. [1] describe a general review of conference papers that places innovative waste management in a larger context of smart cities and sustainability. Method: a non-systemic review, and synthesis, to collect and summarize conference papers that considered sustainability, resource use, and urban technologies. Findings: the review identifies thematic connections between waste management policies, recycling, principles of circular economy, and plastic pollution, and demonstrates where innovation technologies align with policy and behavioral aims. Research gap: the review is not comprehensive, nor does it provide a robust inclusion criteria for developing foundational empirical principles or policy prescriptions that make a concrete connection between technological interventions and the principles of circular economy.



Concari et al. [9] present a large-scale bibliometric and text-mining review of 2,061 publications, to understand recycling behavior and smart city policies. Methodology: bibliometrics using automated mapping, and topic extraction to categorize thematic clusters, and research trends. Findings: evidence supports a link between smart city policy and community recycling behavior and identified three research themes of higher interest (i.e. policy, behavior, and technology). Research gap: while the bibliometric review provides a description of broad thematic trends, there is no connection to actionable design of systems, or tested interventions specific to the engagement of citizens.

D'Amico et al. [10] provides a theoretical review of ICT's contribution to urban metabolism digitalization and transitioning from products to waste in a circular way. Method: thematic synthesis of literature and example case studies that describe digital tracking, monitoring, management of resource flows, etc. Outcome: ICT tools could enable circular economy transitions by improving traceability, material recovery, and process coordination between stakeholders. Research gap: empirical validation and published case studies quantifying (or monetizing) environmental or economic benefits from ICT-enabled circular interventions in practice are lacking and need to be better available from urban contexts.

Ahmad et al. [6] offers a structured review of blockchain applications in the waste management system, which utilizes distributed ledgers for traceability, responsibility, and automatic compliance. Method: survey of blockchain proposals and develop of conceptual Smart contracts application and workflow integration in the WMS. Findings: blockchain is characterized as promising to enable secure, and auditable tracking waste streams, as well as enforcing illegal handling regulations. Gaps in research: limited empirical piloting studies, which evaluate blockchain's performance bottlenecks, privacy implications, transaction costs, and inter-operability with current municipal legacy systems.

Santibañez et al. [35] conduct a bibliometric review of circular economy scholarship focused on smart cities from 2013-2022, specifically, policy levers that enable waste prevention and material recovery. Method: quantitative bibliometric mapping to identify influential works and research themes. Findings: evidence that circular economy policies materially reduce waste through reuse and recovery strategies, as well as the identification of policy research clusters. Research opportunity: the need for mixed-method studies that combine policy analysis with technical assessments of WMS practice implementation in order to establish causal relations between policy instruments and measurement of waste outcomes.

Kannan et al. [36] introduce the WMS 4.0 framework, which combines Industry 4.0 technologies (including sensors, IoT, blockchain, data analytics, and computational intelligence) with socio-technical aspects of waste management (smart people, smart cities, innovative enterprises, smart factories). Research approach: an integrative literature review and expert validation to establish a the beginning of a multi-dimensional research agenda. Findings: a conceptual framework that situates technological possibilities in the organizational and social substrates of waste systems. Research opportunity: few empirical studies have tested the WMS 4.0 framework within or across the four pillars related to business models, governance arrangements, or citizen adoption beyond urban pilots.

Sodiq et al. [4] provide a review of the treatment of food waste in smart cities and the socio-environmental trade-offs associated with technological treatment strategies, like food waste disposers. Method: thematic synthesis of studies addressing food-waste treatment and effects on infrastructure. Finding: while these leave food waste out of landfills - notably where food waste composes a significant portion of the waste stream - and could cause sewer system issues, coordination between policy and engineering implications could address appropriate uses of these technological systems for food waste treatment. Research gap: there is little research on long-term techno-environmental system assessments or on eco-designing policies that aide in pairing the benefit of disposal of waste (food waste) with cost to infrastructure and human health.

Sodiq et al. [4] make a significant contribution to the emerging scholarship on food waste management practices employed in smart cities, particularly the potential social-environmental trade-offs associated with technology advances (for, e.g., food waste disposers). Method: A thematic syntheses of literature that has considered food waste treatment and externalities on infrastructure. Findings: While disposers can effectively reduce food waste to landfills- in particular when the food waste represents a significant share of municipal solid waste leading to transport costs and landfill volume- there are potential negatives to sewer infrastructure and consideration of consequences can provide a framework for coordinated policies and engineering solutions. Gap in literature: A dearth of long-term techno-



environmental evaluations and policy design studies, which consider the tradeoffs between waste diversion benefits and external costs, namely the costs to infrastructure and public health.

Research Gap

Although there have been significant developments in smart waste management, IoT integration, and robotic automation, the review of 37 studies demonstrates that adopting fully autonomous, intelligent, and adaptable robotic systems for waste collection and sorting in public settings remains an emerging, less explored area. The bulk of the work that is out there focused on smart bin designs, IoT-based monitoring, and data-driven route optimization. Overall, there is still a lack of a fully-integrated system that can autonomously manage the entire waste handling process, including detection, pickup, waste classification, and final waste disposal.

Within each the examined studies, the reviewed articles identified a lack of integration of Artificial Intelligence (AI), Robotics, and IoT in to a single framework. Although several articles described incorporating IoT-based smart bins for monitoring an alerting, they ultimately employed human-operated collection vehicles for physically removing waste from the smart bins. When examining robotic arms or mobile platforms, predominantly those examined in lab settings, they may integrate robotics to collect waste and sorting waste, but many do not integrate IoT design to communicate with the waste management system. As a result, there is an disconnect dividing the cyber (IoT) and physical (robot) components, thus limiting the ability to scale and to coordinated management over larger areas of the public environment.

A separate area with a critical gap is in the waste classification. Many systems currently utilize only basic sensor-based segregation that uses moisture or inductive sensors to classify waste into only broad categories, such as dry, wet, or metals. There has been useful work on vision-based classification using deep learning techniques (such as CNNs or YOLO), effective in laboratory experiments but have yet to transfer to true outdoor environments where lighting, occlusion, and odd-shaped waste challenge the application of recognizing waste. This highlights the need of a robust model for AI-driven waste classification models fused with sensor data in real-time or nearly real-time applications.

Similarly, most of the systems reviewed, operated only in controlled or simulated environments, limiting real-world adoption. Limited studies have addressed aspects of feasible operation, such as dynamic obstacle, variable terrain, battery life, or changing weather conditions. Uncertain public settings, energy-efficient systems, and autonomous navigation in the waste collecting state are largely a research gap without knowing aspects of on-site efficient path planning, dynamic obstacle avoidance, and decision making using reinforcement learning or hybrid controls.

The communication and fleet management dimension of autonomous waste robots remains under-researched: only limited discussion has examined the coordination of multiple robots, cloud synchronization, or the analytics of real-time data for predictive maintenance and operational route planning. The introduction of edge computing, as well as low-power IoT protocols and 5G connectivity, would also unlock the scalable nature of such systems. All of this under-research suggests immaturity in this area.

Future studies should examine holistic unified AI-IoT-robotics models for autonomous waste collection processes, vision-assisted classification devices under a variety of conditions, energy-efficient and adaptive navigation designs, and frameworks for multi-robot coordination in the large-scale and sustainable waste management of smart cities.

III. DISCUSSION

The survey of current research on intelligent waste management systems shows a fast-moving but disjointed research landscape. There is consensus among researchers that, in the future, waste management will incorporate robotics, IoT, and AI, but most efforts to date are concentrated on these themes separately. Integrating these innovations into a seamless or fully autonomous system continues to be an ongoing challenge and consideration for researchers and practitioners alike. This section highlights some of the key considerations, comparisons, and technology implications from the review, in the context of a comprehensive robotic waste management system such as WasteXpert Auto.

One of the significant findings arising from the review is that the vast majority of systems are concerned with monitoring and not action. IoT-based waste management systems are designed around smart bins that may contain, ultrasonic sensors, GSM modules, and cloud dashboards to monitor fill levels and notify authorities. While the systems



increase awareness and scheduling efficiency, they still rely on human to collect the waste. Alternatively, robotic systems, that can example include autonomous sweepers or manipulators, are focused on the physical (i.e., robotic actuation) task of waste collection, but without real-time data connections, and centralized monitoring. Hence, the point of discussion will be needed would be to incorporate IoT enabled data intelligence with robotic actuation to fundamentally enable autonomous waste collection.

Another consideration relates to both the autonomy and adaptability of existing systems. Most prototypes reported on operate within structured or semi-structured domains, such as an indoor campus in a building or on a controlled test bed. However, public outdoor environments present very un-structured, un-predictable, and dynamic conditions——pedestrians, uneven surfaces, climate and weather variation, and irregularly viewed waste placement. The current approaches employing ultrasonic or IR-based systems have very little adaptation abilities. Emerging approaches, like LiDAR base mapping, stereo vision, or deep reinforcement learning approaches for adaptive navigation, show a great deal of potential to advance waste management robotic systems, but have gone largely un-explored. Distinctly, future robotic systems must evolve from simply following a preprogrammed route, to re-learning responses to dynamic environmental information to allow navigation to adapt to environmental changes.

From the perspective of AI, waste classification and segregation is a highly complex yet impactful subject matter. The most elementary sensor-based segregation methods—using induction and moisture sensors—allow simple triaging of materials into metallic, dry, and wet categories but are fundamentally concerned with those primitive categories and are incapable of acting on a more complex mixed waste classification. Recent technologies based on computer vision and convolutional neural networks, or CNNs, have demonstrated high levels of accuracy in laboratory settings recognizing recyclable materials, such as plastics, paper, glass, and other recyclable metals. However, their use in outdoor mobile robots is limited because of their computational demands, energy consumption, and environmental variability. By assessing deep learning architectures that do not require sophisticated computational processing (e.g., MobileNet, Tiny-YOLO) and embedding lightweight, energy efficient computing in edge devices, we can enhance the recognition of waste while improving energy efficiency on-board. The optimization of AI for embedded devices is clearly a direction for future development to integrate AI perception and embedded hardware.

Another noteworthy discussion topic concerns the sustainability of systems and the merit of energy efficiency. Most current robots use either battery-powered DC motors or servomechanisms in the form of off-the-shelf, standard servos, where no power optimizing strategy has been implemented. Running in large public, accessible areas will deplete the energy reserve of robots within a short period of time, resulting in a limited amount of run time. Adding integration for solar-assisted charging, low powered microcontrollers, and a more intelligent power management algorithm would lead to an enhanced operational autonomy. Additionally, developing docking or wireless charging stations as part of urban assets would allow autonomous waste robots to charge and recommence work autonomously and without human intervention in the field, which allows for the realization of the ultimate goal of sustainable 24×7 urban cleanliness.

The communications and data management components should also be considered. Multiple IoT-based monitoring platforms may utilize either GSM or Wi-Fi for transmitting real-time information, but these communication methods might not provide reliable latency and connectivity under open urban conditions. The introduction of more connectivity styles (e.g., LoRaWAN, NB-IoT, or 5G) would be beneficial because those alternatives could provide wider range and certainly would be more reliable than GSM or Wi-Fi, while consequently using minimal energy. Additionally, future monitoring systems could take advantage of a mixture of local and cloud data processing, where each sensor node would be capable of local data processing in order to make immediate responses, while aggregate information could be analyzed in the cloud for long-term optimization. This data management architecture with a dual layer allows for both speed of responsiveness and scalability that would be needed for institutional-level applications.

Moreover, the area of multi-robot collaboration is an evolving area with great possibility and good prospect. At the moment, most systems work as standalone prototypes covering small areas. Alternatively, a fleet of autonomous waste robots working together and supervised from a central dashboard in the Internet of Things (IoT), could able to change cleaning assignments based on waste density data in real time, and by using geographic mapping. Swarm intelligence algorithms, or MARL could be used to help robots communicate, negotiate routes, and optimize resource usage for thrifty operation.



In summary, the authors emphasize the importance of progressing from standalone smart devices to intelligent and collaborative ecosystems with it in garbage handling. The conceptual framework of WasteXpert Auto contributes to this evolution as it integrates multidisciplinary robotic automation, intelligent perception, connected IoT systems, and sustainability in a single system. WasteXpert Auto would reduce reliance on human input while increasing accuracy, safety, and environmental impacts in waste management processes. By addressing, at least in part, the technological, communicative, and adaptational issues that are often present in current research, WasteXpert Auto represents a creative approach to the next generation of waste management in smart cities.

IV. CONCLUSION

As the complexities associated with urban waste management increase, the call for smart, innovative, and sustainable waste management schemes has been identified beyond the conventional manual collection systems. The recent systematic literature review reviewed 37-inclusive studies that addressed smart waste management strategies using measurements from the Internet of Things (IoT)-based monitoring, machine learning-based waste prediction, route optimization, and robotic automation approaches. The review presents a snapshot of the current state of the literature and reflects the trend to engage artificial intelligence (AI), robotics, and IoT iterative manner with examples; although, most of the projects are not intended to develop fully autonomous waste management systems, they are rather indications of subsystems.

WasteXpert Auto is an exciting and revolutionary next-generation solution that combines multiple technologies into one integrated system. Real-time sensing, autonomous navigation, AI-powered waste classification, and IoT-enabled device monitoring can all function autonomously in public spaces to detect, collect, sort, and dispose of waste—safely and reliably. These technologies lower reliance on human interaction, and increase safety, efficiency, and environmental sustainability. Also, by including GSM and GPS communication modules, we will develop capabilities for real-time location monitoring, system condition monitoring, and predictive maintenance, all which are necessary elements of smart city infrastructure.

Although substantial progress has been achieved in sensors, path planning, and machine learning, there are still many challenges and problems to be solved, such as scalability, energy efficiency, adaptability to heterogeneous environments and team coordination across multiple robots. Continuing to advance these capabilities like scalable edge-computing, energy-efficient robotics, and AI-based decision-making in the field of waste management will be imperative for successful autonomous systems, such as an autonomous waste management robot. Future research in areas of collaborative robotics, such as swarm systems, renewable energy solutions, and/or data-driven predictive analytics research and development, may contribute to environmental clean-up to a whole new level of possibilities and scale with the design and implementation of collaborative robotics systems.

WasteXpert Auto illustrates what wonderful possibilities we can accomplish with the application of robotics, IoT and AI technology for smarter and more sustainable waste management. The ability of continued research and continued technology development on these systems means urban cleaning will become a self-sustaining, automated, intelligent, and sustainable process which leads the way for cleaner, smarter, more sustainable cities.

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