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Smart waste management: A paradigm shift enabled by artificial intelligence

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ABSTRACT

Waste management poses a pressing global challenge, necessitating innovative solutions for resource optimization and sustainability. Traditional practices often prove insufficient in addressing the escalating volume of waste and its environmental impact. However, the advent of Artificial Intelligence (AI) technologies offers promising avenues for tackling the complexities of waste management systems. This review provides a comprehensive examination of AI's role in waste management, encompassing collection, sorting, recycling, and monitoring. It delineates the potential benefits and challenges associated with each application while emphasizing the imperative for improved data quality, privacy measures, cost-effectiveness, and ethical considerations. Furthermore, future prospects for AI integration with the Internet of Things (IoT), advancements in machine learning, and the importance of collaborative frameworks and policy initiatives were discussed. In conclusion, while AI holds significant promise for enhancing waste management practices, addressing challenges such as data quality, privacy concerns, and cost implications is paramount. Through concerted efforts and ongoing research endeavors, the transformative potential of AI can be fully harnessed to drive sustainable and efficient waste management practices.

Introduction

Waste management is a pressing global challenge, with the escalating volume of waste necessitating innovative and sustainable solutions (Amaral et al., 2020; Cheng et al., 2022; Chien et al., 2023; Codinhoto et al., 2023; Horton, 2022; Mahyari et al., 2022; Zhang et al., 2022; Zhou et al., 2020). Current challenges in waste management persist despite advancements in technology and awareness. One significant challenge is the inadequate infrastructure for waste collection and disposal, particularly in developing regions (Chiem et al., 2023). Insufficient funding and resources hinder the establishment of proper waste management systems, leading to illegal dumping and environmental pollution (Bundhoo, 2018). Additionally, there is a lack of standardized waste management practices globally, resulting in varying levels of efficiency and effectiveness across different regions (Olawade et al., 2023a). Another challenge lies in the complexity of waste composition, with the increasing prevalence of non-biodegradable and hazardous materials complicating disposal and recycling processes (Wang et al., 2022). Moreover, issues related to waste segregation and contamination persist, impeding recycling efforts and diminishing the quality of recovered materials (Olawade et al., 2023). Furthermore, inadequate public awareness and education about proper waste disposal practices contribute to improper waste handling and disposal behaviors, exacerbating environmental and health risks (Ziraba et al., 2016).

In recent years, Artificial Intelligence (AI) has emerged as a transformative technology that can revolutionize waste management

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practices and challenges (Abdallah et al., 2020a; Chew et al., 2023; Hojageldiyev, 2019; Karbassiyazdi et al., 2022; Kumari et al., 2023; Maiurova et al., 2022; Mohammadiun et al., 2021; Ramya et al., 2023; Ye et al., 2020; X. Zhu et al., 2019). By leveraging AI's capabilities in data analysis, pattern recognition, and decision-making, waste management systems can be optimized to enhance efficiency, resource utilization, and environmental sustainability (Aniza et al., 2023; Hu et al., 2022; Huang and Koroteev, 2021; Paul and Bussemaker, 2020).

Current trends in AI applications within waste management demonstrate its growing impact and potential (Di Vaio et al., 2022; Pallathadka et al., 2023; Papagiannis et al., 2021; Yigitcanlar et al., 2020). From intelligent waste collection systems to advanced sorting technologies and predictive analytics, AI is reshaping the waste management landscape in numerous ways (Bamakan et al., 2022; Hoque and Rahman, 2020; Krishna and Sharma, 2023; Kulisz and Kujawska, 2020; Wilts et al., 2021; C. Zhang et al., 2022).

The first prominent trend is the implementation of AI in waste collection processes. Traditional waste collection methods often suffer from inefficiencies such as suboptimal routing and irregular schedules (Cubillos, 2020). However, AI-powered systems are addressing these challenges by optimizing waste collection routes (Solano Meza et al., 2019; Yadav and Karmakar, 2020; Yu et al., 2021). Smart bin systems equipped with sensors and AI algorithms can monitor waste levels in real-time, enabling efficient collection planning and resource allocation (Hussain et al., 2020; Pamintuan et al., 2019). Route optimization algorithms, driven by AI, analyze historical data, traffic patterns, and waste generation rates to determine the most efficient routes for waste collection vehicles (Ghahramani et al., 2022; Lin et al., 2022). Dynamic scheduling algorithms further optimize collection schedules based on real-time data, ensuring timely waste removal, and reducing operational costs.

Another significant trend is the integration of AI in waste sorting operations. Conventional waste sorting methods often rely on manual labor, which can be time-consuming and error-prone (Das et al., 2019; Guo et al., 2021). AI technologies, such as image recognition and machine vision, are increasingly being employed to automate and improve waste sorting accuracy (Weisheng Lu et al., 2022; Zhang et al., 2021). Advanced image recognition algorithms can analyze visual data and identify different waste materials with high precision, facilitating efficient segregation of recyclables, organic waste, and non-recyclables (Dong et al., 2022; S. Kumar et al., 2021; Majchrowska et al., 2022; Sundaralingam and Ramanathan, 2023). Additionally, robotic sorting systems equipped with AI algorithms can effectively separate and sort waste materials, streamlining the sorting process, and increasing recycling rates (N. M. Kumar et al., 2021).

AI is also playing a crucial role in waste recycling by optimizing various stages of the recycling process. Material identification and sorting technologies driven by AI enable accurate identification and separation of recyclable materials, maximizing resource recovery and minimizing waste contamination (Wu et al., 2023). Process optimization models, powered by AI, analyze data on recycling parameters, such as temperature, pressure, and composition, to identify optimal operating conditions and improve efficiency. AI-driven quality control and inspection systems ensure the production of high-quality recycled materials by detecting defects, contamination, and non-compliance. Furthermore, robotics and automation, guided by AI algorithms, streamline recycling operations, reducing human error, increasing throughput, and improving overall recycling efficiency (Onoda, 2020).

Waste monitoring is another area where AI is making significant advancements (Khanal et al., 2023). Real-time monitoring systems, integrated with IoT devices and sensor networks, collect, and analyze data on waste generation, collection, and disposal processes (Sharma et al., 2021). AI algorithms process this data, providing actionable insights for optimizing waste management operations. Predictive analytics models leverage historical and real-time data to forecast waste generation patterns, optimize resource allocation, and enable data-driven decision-making in waste management practices (Ghanbari et al., 2023; Lu et al., 2021; Nguyen et al., 2021; Rosecký et al., 2021; Soni et al., 2019a; Sunayana et al., 2021; Zhu et al., 2023).

While the integration of AI in waste management offers numerous benefits, some challenges and limitations must be addressed (Sharma et al., 2022). These include ensuring data availability and quality, addressing privacy and security concerns, managing the cost of implementation and infrastructure requirements, and considering ethical implications (de Sousa et al., 2019). Collaborative efforts between waste management agencies, technology providers, researchers, and policymakers are crucial for overcoming these challenges and fostering responsible and sustainable use of AI in waste management (Abdullah et al., 2019; Oyedotun and Moonsammy, 2021).

The use of AI in waste management and practices is rapidly evolving, driven by current trends and advancements. From optimizing waste collection and sorting processes to enhancing recycling operations and enabling data-driven decision-making, AI has the potential to transform waste management into a more efficient, sustainable, and environmentally conscious endeavor. By harnessing the power of AI, waste management systems can tackle the growing challenges associated with waste and contribute to a greener and more sustainable future (Banjar et al., 2022; Delanoë et al., 2023; Güleryüz, 2020; Herath and Mittal, 2022; Kamali et al., 2021; Kurniawan et al., 2022; Murthy and Ramakrishna, 2022; Rafew and Rafizul, 2021; Rapati et al., 2023; Wang et al., 2023). This review aims to explore the current state of AI applications in waste management and practices. It examines how AI can enhance various aspects of waste management, including waste collection, sorting, recycling, and monitoring. The review discusses the benefits, challenges, and prospects of incorporating AI into waste management strategies to create more sustainable and efficient processes.

Methodology

To compile this review, we conducted a comprehensive search across academic databases, research papers, industry reports, and relevant publications. Specifically, we retrieved articles from Google Scholar and Scopus. Fig. 1 shows the flow chart for literature search strategy. Key terms such as "artificial intelligence," waste generation," "intelligent waste management system," "smart waste management," "urban waste management" etc. were used to identify relevant studies and examples of AI applications in waste management. The selection criteria includes abstract, title and keywords.

The database contained 246 items with publication years ranging from 2021 to 2023 as shown in Table 1. This window of time made it possible to find the most relevant and up-to-date publications for the research's purpose. Before the final analysis, 175 (71.14 %) ineligible articles were carefully eliminated to achieve reliability, and 71 (28.86 %) articles published between 2021 and 2023 that had undergone critical analysis were added to the study to provide an overview of the current state of AI in waste management practices.

The selected sources were critically analyzed and synthesized to provide an overview of the current state of AI in waste management practices. The sections of this review will delve into specific areas where AI is being employed to revolutionize waste management practices, highlighting the benefits and challenges associated with each application. By exploring the potential of AI-driven approaches, this review aims to provide insights into the transformative power of AI in waste management and inspire further research and innovation in this field.

Artificial intelligence techniques in waste management

To manage and handle waste efficiently, artificial intelligence (AI) techniques have been widely utilized as highlighted in Fig. 2. As a result, it is capable of handling large amounts of waste data, generating efficient and reliable results, while providing the opportunity to automate a

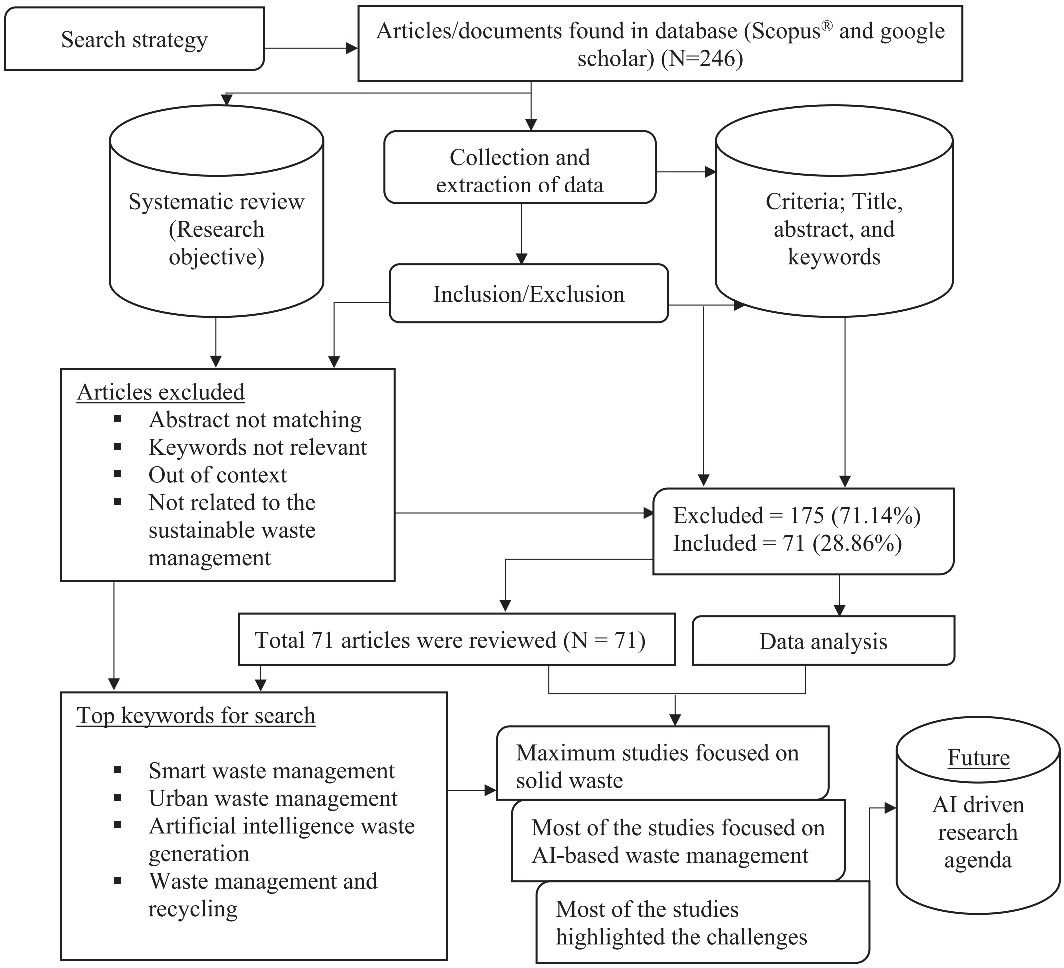

Fig. 1. Literature search strategy flowchart.

Table 1
Research papers inclusion and exclusion statistics.

Serial Number	Keywords used for search	Items in Google Scholar			Items in Scopus®			Total number of included items	Total number of excluded items
		2021	2022	2023	2021	2022	2023		
1	Intelligent waste management system	3	5	4	3	5	1	5	16
2	Artificial intelligence waste generation	2	3	2	4	5	3	6	13
3	Smart waste management	3	4	3	2	3	2	8	9
4	Artificial intelligence applications	5	2	4	3	3	3	6	14
5	Urban waste management	2	4	2	3	5	2	7	11
6	Solid waste management	2	3	2	1	1	1	1	9
7	Waste management ecosystem	4	3	3	2	4	2	4	14
8	IOT based waste management system	1	3	1	1	3	3	5	7
9	Waste management policies	4	2	4	1	2	2	3	12
10	Waste management and recycling	3	3	3	2	3	2	6	10
11	Waste management collection planning	5	3	3	2	3	3	6	13
12	Waste management planning of energy	1	3	1	0	3	1	0	9
13	Waste management systems machine learning approach	3	2	3	4	2	3	3	14
14	e-waste management environmental planning	1	3	1	2	4	1	5	7
15	Transfer learning smart waste management system	0	3	1	1	2	1	0	8
16	Sustainable solid waste management practices	3	2	3	2	3	2	6	9
		42	48	40	33	51	32	71	175

variety of processes. Several AI techniques are widely employed in the waste management sector, including waste collection, waste sorting, bin-level sorting, waste treatment, and waste management planning (Chen, 2022; Xiang et al., 2021). There has been a drastic expansion of the use of AI in recent years, and various governments and organizations are continuously investing in different AI innovations. (Abdallah et al., 2020b; Yigitcanlar and Cugurullo, 2020).

AI technology adoption has soared, and the global market size is forecast to grow from USD 428.00 billion in 2022 to USD 2,025.12 billion in 2030 (FBI, 2023). There have been several AI techniques

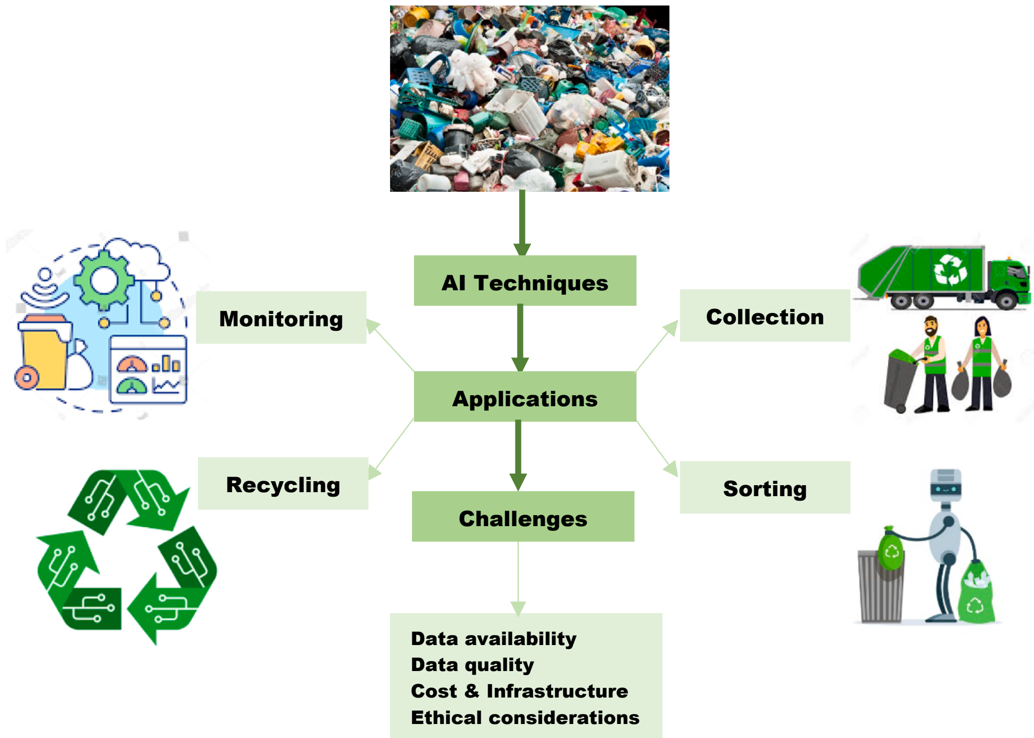

Fig. 2. Highlight of Artificial Intelligence Techniques in Waste Management.

integrated into waste management over the years, including linear regression; support vector machines (SVMs); decision trees (DTs); artificial neural networks (ANNs); and genetic algorithms (GAs). A description of these AI techniques follows;

i. Linear regression (LR)

It is a supervised machining learning method in which training datasets are used to determine the linear relationship and to make predictions regarding target values (Huang et al., 2023). The linear relationship is depicted using estimated coefficients which are associated with independent variables.

LR models are widely used in solid waste management (SWM) as single regression models – with one variable – and multiple linear regression models (MLR) – with multiple variables. As SWM are often dependent on multiple variables, an MLR is more appropriate (Abdallah et al., 2020b). There are numerous advantages of linear regression models, including their efficiency, ease of use, and interpretability. However, they do not provide flexibility in practice and cannot accommodate nonlinear relationships. Utilizing LR models has proven to be an effective means of optimizing waste generation (Abdulredha et al., 2018; Abdoli et al., 2012; Azadi & Karimi-Jashni, 2016; Chhay et al., 2018; Golbaz et al., 2019; Montecinos et al., 2018; Wei et al., 2013), waste management planning (Ferreira et al., 2017), waste collection and vehicle routing (Montecinos et al., 2018), and waste treatment and disposal (Hosseinzadeh et al., 2020).

ii. Support vector machine (SVM)

In recent years, SVMs have become more popular as supervised machine learning algorithms due to their relevance in the analysis of large datasets (Gholami & Fakhari, 2017; Meza et al., 2019). Due to their capacity to optimize the margin (distance between data points), SVMs act as non-parametric classifiers. In an N-dimensional space (where N is the number of features), the main objective of SVM algorithms is to locate a hyperplane (decision boundary) that uniquely separates the data points. In addition to solving classification-based problems, SVMs have also demonstrated outstanding performance in regression problems, outperforming many regression-based algorithms (Abdallah et al., 2020b). In addition to being memory efficient, SVMs perform better when the classes are separated by hyperplanes. For large datasets, however, SVMs are not suitable, as they rely on five-fold cross-validation rather than probability estimation. In waste generation, SVMs have been used (Abunama et al., 2019; Altin et al., 2023; Ayeleru et al., 2021; Cha et al., 2023c; Graus et al., 2018; Kumar et al., 2018; V. Sousa et al., 2019), bin level detection (Morison et al., 2013), waste collection and vehicle routing (V. Sousa et al., 2019), waste sorting and treatment (Singh and Satija, 2018; Zarei et al., 2023; Zhu et al., 2022), waste sorting and identification (S. Zhu et al., 2019), and waste management planning (Zhang and Yan, 2021).

iii. Decision Tree (DT)

DT is a tree-like non-parametric supervised machine learning technique that is applied to both classification and regression-based problems. It is a hierarchical structure with a root node (the base of the tree structure), a decision node (the consequences of the decision), and a leaf node (the split points), and each branch of the tree is called a "branch." DTs are not only commonly used in a wide range of applications, but are also known for their robustness and interpretability (Costa and Pedreira, 2023). Although DT algorithms are simple, flexible, easy to interpret, and efficient in predicting and training datasets, they are mostly heuristic-based and do not have a single representative algorithm. However, DTs are commonly used to optimize waste generation predictions (Gulghane et al., 2023; Wenjing Lu et al., 2022; Singh and Uppaluri, 2022), and waste management planning (Lu, 2019; Massoud et al., 2023).

iv. Artificial neural network (ANN)

ANN is a computational machine-learning model that mimics the behavior of nerve cells in the human brain (Kanwisher et al., 2023). An

ANN consists of a set of nodes that are divided into input, hidden, and interconnected output layers. Several domains, such as computer vision, natural language processing, speech recognition, and others, have achieved remarkable success with neural networks. As a result of their ability to comprehend complex patterns from large datasets, adapt to new data, and simulate non-linear relationships, these models are extremely effective in solving a wide variety of real-world problems. ANN is gaining a lot of attention in the waste domain because they allow the storage of information across all node layers. They work with missing information, even if some node layers have defects, and can perform more than one task simultaneously. However, they are prone to overfitting, hardware dependent (requires a significant amount of storage), and require a significant amount of training time for data. ANN models are used to optimize waste generation (Coskuner et al., 2021; Fan et al., 2020; Jassim et al., 2023, 2022; Kannangara et al., 2018; Magazzino et al., 2021; Ribic et al., 2019; Soni et al., 2019b), waste sorting (Adedeji and Wang, 2019; Melinte et al., 2020; Mohammed et al., 2022), and waste management planning (Lu et al., 2023; Singh, 2019).

v. Genetic algorithm (GA)

GA is a heuristic-based search and optimization technique. A genetic selection principle underlies its application (Lambora et al., 2019). The algorithm is a subset of evolutionary algorithms that are utilized in computation. It utilizes the concepts of genetics and natural selection to solve real-world problems. There are three main components of GA: mutation, selection of the fittest, and crossover (Abdallah et al., 2020b). Even though GA can provide accurate and robust results, has an outcome that improves over time, and is readily programmable, it is not suitable for solving simple problems, and requires additional care in the construction of models (Toutouh et al., 2019). Several studies have applied GAs to optimize waste management planning (Thaseen et al., 2023) and vehicle routing (Yu et al., 2022; Zhang et al., 2022).

AI in waste collection

The waste collection plays a crucial role in managing waste efficiently and ensuring a clean and sustainable environment (Assef et al., 2022; Kaya et al., 2021; Martin-Rios et al., 2021). With the advancements in Artificial Intelligence (AI), waste collection processes have been revolutionized by incorporating smart bin systems, route optimization algorithms, dynamic scheduling, and demand prediction models (Sharma and Vaid, 2021). These advancements are summarized in Fig. 3. These AI-driven technologies are shaping the future of waste collection by improving operational efficiency, reducing costs, and minimizing environmental impacts (Xu et al., 2021).

AI-driven waste management solutions tackle scalability challenges by leveraging automation, data analytics, and predictive capabilities (Bibri et al., 2024). These technologies enable efficient resource allocation, optimizing waste collection, sorting, and recycling processes at scale. By automating tasks such as route planning and sorting, AI systems enhance operational efficiency, allowing waste management infrastructure to handle larger volumes of waste without proportional increases in resources (Nwokediegwu et al., 2024). Furthermore, AI's predictive capabilities anticipate future waste generation patterns, facilitating proactive decision-making and resource allocation to accommodate growing waste volumes effectively. Overall, AI-driven solutions provide scalable and adaptable approaches to address the escalating global waste challenge.

Smart bin systems

Smart bin systems have gained significant traction in recent years due to their ability to optimize waste collection processes (Ahmed et al., 2022; Karthikeyan et al., 2021). These systems are equipped with sensors that monitor the fill levels of bins in real time. The collected data is then analyzed using AI algorithms to determine the optimal collection routes and schedules. Current trends in smart bin systems include the integration of advanced sensors, such as ultrasonic sensors and weight sensors, to provide more accurate data on fill levels (Dubey et al., 2020a). Additionally, smart bins are being equipped with connectivity features, such as IoT technology, to enable seamless communication between the bins and waste management authorities (Dubey et al., 2020b; Zhang et al., 2020). This connectivity allows for real-time monitoring, remote management, and proactive maintenance of the bins. Furthermore, smart bin systems are incorporating machine learning algorithms to improve accuracy in fill-level predictions and optimize waste collection operations even further (Bijos et al., 2022).

Route optimization

Route optimization is a key aspect of waste collection, aiming to minimize travel time, fuel consumption, and vehicle emissions. Recent

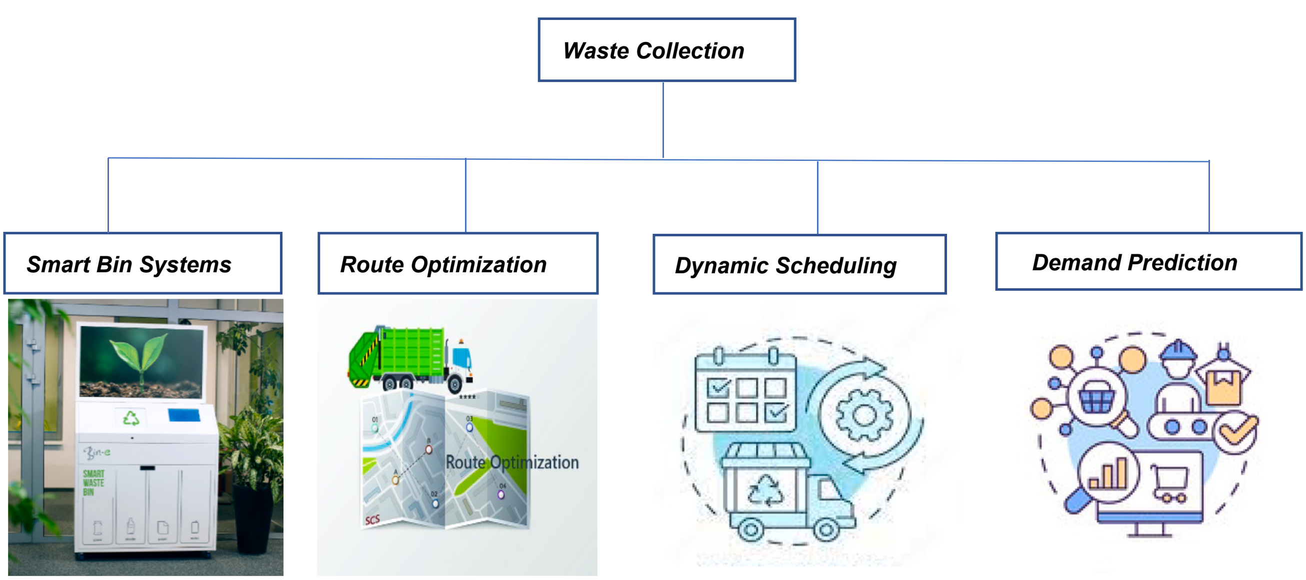

Fig. 3. Applications of AI in Waste Collection.

trends in route optimization involve the integration of AI technologies, such as machine learning and optimization algorithms (Agrawal et al., 2021). These algorithms leverage real-time data sources such as GPS tracking, traffic conditions, historical collection data, and weather forecasts to dynamically adjust routes based on current conditions and demand. Also, the algorithms consider various factors, including real-time traffic data, historical waste generation patterns, and weather conditions, to generate the most efficient collection routes (Ahmad et al., 2020). Advanced machine learning techniques, such as deep learning, are being employed to learn from large datasets and predict traffic patterns, optimize routes in real time, and adapt to dynamic conditions (Ghoreishi and Happonen, 2020). Moreover, route optimization algorithms are incorporating dynamic rerouting capabilities to adjust collection routes on the go based on real-time data, such as traffic congestion or new waste generation events (Anh et al., 2020). This flexibility allows waste management companies to respond quickly to changes and optimize their collection operations.

Moreover, by integrating AI algorithms with real-time data sources, such as population density, traffic patterns, and waste generation rates, waste management systems can dynamically adjust collection routes and schedules to maximize efficiency and resource utilization (Ghoreishi and Happonen, 2020). AI-driven route optimization algorithms analyze various factors, including traffic congestion, proximity to waste generation sources, and historical collection data, to determine the most efficient routes for waste collection vehicles. Moreover, predictive analytics models can forecast waste generation patterns based on historical data and external factors, enabling waste management authorities to anticipate demand and optimize collection schedules accordingly (Munir et al., 2023). By considering these factors and leveraging AI technologies, waste management systems can minimize travel time, fuel consumption, and vehicle emissions, while ensuring timely and efficient waste collection services for communities.

Dynamic scheduling

Dynamic scheduling involves adjusting waste collection schedules based on real-time data and changing conditions. The current trends in dynamic scheduling focus on real-time data integration and advanced analytics. Waste management companies are leveraging AI technologies to collect and analyze data from various sources, such as smart bin systems, traffic monitoring systems, and weather forecasts. By combining these data sources, AI algorithms can dynamically optimize collection schedules, allocate resources efficiently, and adapt to fluctuating waste generation patterns (Sharma and Vaid, 2021). Advanced analytics techniques, including predictive modeling and data mining, are used to identify patterns, trends, and correlations in the collected data, enabling more accurate and proactive scheduling decisions (Fang et al., 2023; Niska and Serkkola, 2018; Solano Meza et al., 2023). Additionally, dynamic scheduling is being integrated with mobile applications and communication platforms, enabling real-time updates and notifications for waste collection personnel, and improving coordination between different stakeholders (Narayan, 2021; Nkwo et al., 2021; Nowakowski et al., 2020; Nowakowski and Pamuła, 2020; Sheng et al., 2020; Shukla and Hait, 2022).

Dynamic scheduling plays a vital role in waste management by allowing collection schedules to adapt in real-time based on changing conditions and demand. AI facilitates real-time adjustments in collection schedules by continuously analyzing various data sources, including historical collection data, current bin fill levels, traffic conditions, weather forecasts, and population density (Reza, 2023). Using AI algorithms, waste management authorities can dynamically optimize collection routes and schedules to ensure efficient resource allocation and timely waste collection (Ahmad et al., 2020). For example, if a particular area experiences higher-than-expected waste generation or traffic congestion, AI algorithms can reroute collection vehicles to prioritize those areas and minimize service disruptions. By leveraging AI-driven dynamic scheduling, waste management authorities can improve operational efficiency, reduce costs, and enhance service quality, ultimately contributing to a more sustainable and resilient waste management system.

Demand prediction

Demand prediction models utilize AI techniques to forecast waste generation rates in different areas (Cagurungan et al., 2021; Mishra et al., 2021; Oguz-Ekim, 2021; Singh, 2019). Current trends in demand prediction involve the integration of various data sources and the use of advanced machine-learning algorithms (Cha et al., 2023a). Waste management companies are incorporating data from sources such as social media, online platforms, and IoT sensors to capture real-time information on waste generation patterns (Shahidzadeh et al., 2022). Machine learning algorithms, including ensemble learning and deep learning models, are employed to analyze the collected data and make accurate predictions (Akanbi et al., 2020). These models consider factors such as population density, demographic data, historical waste generation rates, and external factors like events or holidays to forecast waste generation (Cha et al., 2023b, 2022, 2021). By accurately predicting demand, waste management companies can optimize collection resources, allocate personnel and vehicles efficiently, and adjust collection schedules accordingly (Vu et al., 2019a, 2019b).

Demand prediction models play a crucial role in waste management by providing insights into future waste generation patterns, enabling authorities to optimize resource allocation and operational planning (Chang et al., 2011). These models leverage AI techniques to analyze historical data on waste generation, demographic trends, economic indicators, and environmental factors. By identifying patterns and correlations in these data sources, AI-driven demand prediction models can forecast waste generation rates with greater accuracy and granularity (Hassan et al., 2023). The key benefits of these models include improved operational efficiency, better waste collection scheduling, reduced resource wastage, and enhanced responsiveness to changing demand patterns (Kaipia et al., 2013; Sallam et al., 2023). Additionally, by anticipating fluctuations in waste generation, authorities can proactively allocate resources, implement targeted waste reduction initiatives, and optimize recycling and disposal processes, ultimately leading to more sustainable and cost-effective waste management practices.

Integrating AI technologies into waste collection infrastructure requires careful planning and consideration to maximize their effectiveness and minimize potential challenges (Andeobu et al., 2022). Firstly, ensuring compatibility with existing systems is crucial to avoid disruption and facilitate seamless integration. This may involve assessing the capabilities of current infrastructure and identifying areas where AI solutions can complement or enhance existing processes. Additionally, waste management authorities must prioritize data integration, as AI relies on accurate and comprehensive data inputs for optimal performance (Yu et al., 2021). This involves aggregating data from various sources, such as sensors, IoT devices, and historical records, to provide insights for decision-making and optimization.

Moreover, comprehensive training and education programs are essential to empower personnel with the necessary skills to operate and maintain AI-driven systems effectively (Olawade et al., 2024a; Olawade et al., 2024b). Investing in employee training not only enhances system performance but also fosters a culture of innovation and continuous improvement within the organization. Conducting a thorough cost-benefit analysis is another critical consideration, as it helps justify the investment in AI technologies by demonstrating their potential long-term value in terms of cost savings, efficiency gains, and environmental benefits. Additionally, scalability and flexibility are essential factors to accommodate future growth and adapt to evolving waste management needs. AI solutions should be designed with scalability in mind, allowing for expansion or modification as demand increases or new challenges emerge (Bibri et al., 2024). Lastly, stakeholder engagement is vital to ensure that AI-driven initiatives align with community priorities and address the needs of all stakeholders, including residents, businesses, and local authorities. By considering these primary considerations, waste management authorities can successfully integrate AI technologies into their operations and unlock the full potential of data-driven decision-making and optimization in waste collection processes.

AI in waste sorting

Waste sorting is a critical step in the waste management process, where different types of waste are categorized and separated for appropriate treatment or recycling (Chen et al., 2021; Latha et al., 2022; Lubongo and Alexandridis, 2022). The integration of Artificial Intelligence (AI) technologies in waste sorting has revolutionized this process by improving accuracy, speed, and efficiency (Anitha et al., 2022; Mahboob, 2022). The following sections explore the current trends and advancements in AI-driven waste sorting technologies:

Automated sorting technologies

Automated sorting technologies employ AI algorithms to identify and sort waste items based on their material composition (Ma et al., 2020). These technologies utilize advanced sensors, such as near-infrared (NIR) spectroscopy, X-ray fluorescence (XRF), and hyperspectral imaging, to analyze the physical and chemical properties of waste items (Bobulski and Kubanek, 2019; Yan et al., 2021). The collected data is then processed by AI algorithms to determine the material composition and sort the waste into appropriate categories. Current trends in automated sorting technologies focus on the integration of machine learning techniques, such as deep learning and neural networks, to improve accuracy and expand the range of sortable materials (Frankowski et al., 2020). By training the AI algorithms with large datasets, these technologies can learn to recognize and sort a wide variety of waste materials, including plastics, metals, paper, glass, and organic waste.

By automating the sorting process, AI-driven systems can quickly and accurately distinguish recyclables from non-recyclables, organic waste, and contaminants, thereby ensuring the purity of recycled materials (Yan et al., 2021). However, several key challenges must be overcome to achieve this effectively. One challenge is the complexity of waste streams, which may contain diverse materials that are difficult to classify accurately (Mookkaiah et al., 2022). Additionally, the presence of contaminants and impurities in waste streams can interfere with the sorting process and reduce the quality of recycled materials (Gundupalli et al., 2017). Furthermore, ensuring the reliability and scalability of AI-driven sorting technologies across different waste management facilities and environments poses a significant challenge. Addressing these challenges requires ongoing research and development efforts to improve the accuracy and efficiency of AI algorithms, as well as investments in infrastructure and training to deploy these technologies effectively in waste management operations.

Image recognition and machine vision

Image recognition and machine vision technologies are gaining significant momentum in waste sorting applications (Baduge et al., 2022; Neelakandan et al., 2022). These technologies utilize AI algorithms to analyze images or video footage of waste items and identify their material composition (KLONTZA, 2023). Recent trends in image recognition and machine vision involve the integration of high-resolution cameras, advanced image processing techniques, and deep learning models (Kakani et al., 2020). These advancements enable precise identification and classification of waste items in real time. By using convolutional neural networks (CNNs) and other deep learning architectures, these technologies can extract detailed features from waste item images, allowing for accurate material identification and sorting (Adedeji and Wang, 2019). Moreover, machine vision systems are being integrated into sorting conveyor belts to detect and sort waste items at high speeds, ensuring efficient and continuous sorting operations (Koskinopoulou et al., 2021).

Robotic sorting systems

Robotic sorting systems combine robotics and AI technologies to automate the waste sorting process (Subramanian et al., 2021). These systems employ robotic arms equipped with sensors, cameras, and AI algorithms to identify and pick waste items based on their material composition (Ahmed and Asadullah, 2020; Shreyas Madhav et al., 2022). Current trends in robotic sorting systems include the integration of advanced gripping technologies, improved sensor capabilities, and enhanced AI algorithms. Grippers with adjustable grasping mechanisms and tactile sensors enable robots to handle a wide range of waste items with different shapes, sizes, and textures (Gal et al., 2021). AI algorithms, such as reinforcement learning, enable robots to learn optimal picking strategies and adapt to varying waste compositions. Additionally, collaborative robots, known as cobots, are being utilized to work alongside human operators, enhancing efficiency and safety in waste sorting operations (Sarc et al., 2019).

On the other hand, the implementation of AI-powered robotics in waste sorting and processing presents various ethical considerations, particularly regarding job displacement and environmental justice (Bag, 2023; Nwokediegwu and Ugwuanyi, 2024). As AI-driven robots automate tasks traditionally performed by humans, there is a risk of job loss and economic disruption, especially for workers in the waste management industry. Additionally, the deployment of AI-powered robotics may exacerbate existing environmental justice issues by disproportionately affecting communities already burdened by pollution and waste facilities. Without proper oversight and regulation, the adoption of AI in waste management could perpetuate inequalities and marginalize vulnerable populations (Comninos et al., 2019). Therefore, it is essential to consider the social and environmental impacts of AI technologies and implement policies that ensure equitable access to opportunities and mitigate adverse effects on workers and communities. Collaborative efforts between policymakers, industry stakeholders, and community representatives are necessary to address these ethical concerns and ensure that AI-powered robotics contribute to sustainable and inclusive waste management practices.

Sensor-based sorting techniques

Sensor-based sorting techniques, enhanced with AI algorithms, significantly enhance the accuracy and efficiency of waste sorting processes by automating and optimizing the identification and separation of different types of materials. These systems employ various sensors, such as near-infrared (NIR), X-ray transmission, and optical sensors, to detect and classify materials based on their physical properties, such as color, size, and composition density (Feng et al., 2022; Gupta et al., 2019). AI algorithms analyze the data collected from these sensors in real-time, allowing for precise identification and sorting of materials, including plastics, metals, paper, and glass. By continuously learning from the data and adapting their classification criteria, AI-driven sorting systems can achieve higher accuracy rates and reduce instances of misclassification (Konstantinidis et al., 2023). This results in fewer contaminants in recycling streams, higher-quality recyclable materials, and increased overall efficiency in the recycling process. Additionally, AI algorithms can optimize the operation of sorting equipment, such as conveyor belts and robotic arms, to maximize throughput and minimize downtime, further improving the overall efficiency of waste sorting operations.

Current trends in sensor-based sorting involve the integration of multiple sensors, including optical sensors, infrared sensors, and electromagnetic sensors, to capture comprehensive information about waste items (Zhao and Li, 2022; Maier et al., 2024). AI algorithms process the data collected by these sensors, allowing for precise identification and separation of waste items into different categories. Furthermore, sensor-based sorting techniques are being enhanced with real-time feedback mechanisms, enabling immediate adjustments in sorting parameters based on the incoming waste stream (Koinig, 2023). This adaptability ensures accurate and efficient sorting even when faced with varying waste compositions. These trends in AI-driven waste sorting technologies focus on improving accuracy, speed, and adaptability. By integrating advanced sensors, image recognition, machine vision, robotics, and machine learning algorithms, waste sorting processes become more efficient, reduce contamination, and increase the quality of recycled materials (Mookkaiah et al., 2022). As technology continues to advance, these AI-driven sorting technologies will play a vital role in promoting a circular economy and sustainable waste management practices (Kutty and Abdella, 2020; Dash and Sharma, 2022; Wilson et al., 2021).

AI in waste recycling

Waste recycling is a critical component of sustainable waste management practices, and Artificial Intelligence (AI) technologies are playing a significant role in improving various aspects of the recycling process (Erkinay et al., 2021). From material identification and sorting to process optimization, quality control, and robotics and automation, AI is driving innovation and efficiency in waste recycling (As shown in Fig. 4).

Material identification and sorting

Accurate identification and sorting of waste materials are essential for efficient recycling (Chauhan et al., 2023; Lee and Lim, 2022). AI-based systems utilize advanced technologies such as machine learning, computer vision, and spectroscopic analysis to identify and sort different types of materials. Current trends in material identification and sorting involve the integration of AI algorithms with high-resolution cameras, hyperspectral imaging, and advanced sensors. These technologies enable more precise material identification, especially for complex waste streams or mixed materials. Machine learning algorithms, including deep learning models such as convolutional neural networks (CNNs), are employed to recognize and classify various types of materials based on their visual features (Bobulski and Kubanek, 2020; Thanawala et al., 2020; Toğaçar et al., 2020). The use of AI in material identification and sorting ensures faster and more accurate sorting processes, increasing the purity of recycled materials and improving overall recycling efficiency (Al Duhayyim et al., 2022a).

Process optimization

Process optimization in waste recycling involves streamlining and improving various stages of the recycling process to maximize resource recovery and reduce costs. AI technologies enable data-driven decision-making and optimization algorithms to improve the efficiency of recycling operations. Current trends in process optimization involve the integration of AI algorithms with real-time data monitoring, machine learning models, and predictive analytics (Chidepatil et al., 2020). These technologies enable the analysis of operational data, such as equipment

Fig. 4. Applications of AI in Waste Recycling.

performance, energy consumption, and material flow, to identify inefficiencies and optimize process parameters. AI algorithms can learn from historical and real-time data, allowing for adaptive optimization and the ability to predict process outcomes (Golbaz et al., 2019). By optimizing parameters such as temperature, pressure, and residence time, AI-driven process optimization enhances the yield, quality, and sustainability of the recycling process.

Quality control and inspection

Maintaining the quality and purity of recycled materials is crucial for their marketability and reuse. AI-based quality control and inspection systems utilize advanced sensors, computer vision, and machine learning algorithms to detect and remove contaminants from the environment and recycled materials (Modak et al., 2022). Incorporating AI algorithms with advanced sensor technologies such as high-resolution cameras and spectroscopic analysis enables precise identification of contaminants in recyclable materials (Moirogiorgou et al., 2022). These AI-driven systems classify materials based on predefined quality criteria, ensuring accurate sorting and improved efficiency. By continuously monitoring waste streams using near-infrared spectroscopy and computer vision, these systems detect impurities with high precision (Araujo-Andrade et al., 2021). This real-time analysis allows for swift detection and removal of non-recyclable items, ensuring the purity of recycled materials. Additionally, AI algorithms learn and adapt over time, further enhancing classification accuracy and reducing errors. Ultimately, AI-driven quality control systems streamline the inspection process, resulting in higher-quality recycled materials.

Recent advancements in AI-driven quality control systems include the development of sophisticated machine learning models capable of handling large volumes of data and complex material compositions. These models can identify subtle differences in materials and distinguish between recyclable and non-recyclable items with greater accuracy than traditional sorting methods (Pluskal et al., 2021). Additionally, advancements in sensor technology have led to the development of more compact, cost-effective, and versatile inspection systems that can be easily integrated into existing recycling facilities. Overall, AI-driven quality control and inspection systems offer significant potential to enhance the purity of recycled materials, improve recycling rates, and support the transition towards a circular economy.

Robotics and automation

Robotics and automation technologies are transforming the waste recycling industry by automating labor-intensive tasks and increasing productivity (Brintha et al., 2020; Nafiz et al., 2023). AI-driven robots equipped with sensors, cameras, and intelligent algorithms can handle sorting, dismantling, and processing tasks in the recycling process (Bharti et al., 2022). Current trends in robotics and automation involve the integration of AI algorithms with robotic systems to enable precise and efficient waste handling and sorting (Ejimofor et al., 2022). These robots can adapt to different shapes, sizes, and weights of waste items and utilize AI algorithms to identify and sort recyclable materials. Collaborative robots, known as cobots, are being employed to work alongside human operators, enhancing safety and efficiency in recycling operations (Sarc et al., 2019). The use of robotics and automation technologies in waste recycling streamlines operations increases throughput, reduces labor costs, and improves overall resource recovery rates (Mao et al., 2021).

The current trends in AI-driven waste recycling focus on improving material identification and sorting accuracy, optimizing recycling processes, enhancing quality control and inspection, and implementing robotics and automation. These advancements contribute to a more sustainable and efficient waste recycling industry (Rutqvist et al., 2020). However, challenges such as the integration of AI technologies with existing recycling infrastructure, standardization of data and processes, and ensuring the scalability and cost-effectiveness of AI solutions remain areas of focus for ongoing research and development (Bui et al., 2023; K. Wang et al., 2021). Collaboration between researchers, waste management companies, technology providers, and regulatory bodies is crucial to address these challenges and drive the widespread adoption of AI in waste recycling (Monzambe et al., 2019).

Furthermore, current trends also emphasize the importance of data management and analytics in AI-driven waste recycling. The collection, storage, and analysis of large amounts of data generated from sensors, cameras, and other monitoring devices enable continuous improvement and optimization of recycling processes. Advanced data analytics techniques, including machine learning and artificial intelligence, are utilized to derive valuable insights from the data, enabling better decision-making and further enhancing recycling operations.

Another notable trend is the integration of AI technologies with Internet of Things (IoT) devices in waste recycling (Gopalakrishnan, 2019). IoT devices, such as smart sensors and connected machinery, can provide real-time data on waste composition, equipment performance, and operational parameters (Vishnu et al., 2021). By combining AI with IoT, waste recycling systems can become more interconnected and responsive, facilitating proactive maintenance, real-time monitoring, and improved overall process control (Al Duhayyim et al., 2022b; Said et al., 2023).

Moreover, there is an increasing emphasis on the development of AI-driven waste recycling platforms that enable seamless integration and collaboration among different stakeholders in the recycling value chain. These platforms facilitate the sharing of data, knowledge, and best practices, fostering a more transparent and efficient recycling ecosystem. Such platforms can also leverage AI algorithms to provide predictive insights, optimize resource allocation, and enable traceability of recycled materials.

The adoption of AI in waste recycling is not only driven by environmental concerns but also by economic factors. AI technologies have the potential to reduce costs, increase resource recovery rates, and create new business opportunities in the recycling industry. As the demand for sustainable practices and circular economy models continues to grow, AI-driven waste recycling solutions are poised to play a pivotal role in achieving these objectives (Nahaei and Naziri-Oskuei, 2021). Additionally, AI enables the extraction of valuable materials from waste streams with greater precision, facilitating the development of innovative recycling techniques and the production of higher-quality recycled products (Salem et al., 2023). As a result, recycling companies can capitalize on the growing demand for sustainable products and services, fostering the emergence of new business models and market opportunities. Furthermore, AI-driven technologies unlock new revenue streams through data-driven insights and predictive analytics, enabling recycling firms to offer tailored solutions and value-added services to their customers. Overall, the integration of AI into waste recycling processes not only improves economic competitiveness but also drives innovation and growth within the recycling industry, positioning it as a key player in the transition towards a circular economy.

AI-driven robotics and automation technologies offer significant potential to streamline waste recycling operations in several ways (Rakhio, 2024). Firstly, these technologies can automate repetitive and labor-intensive tasks such as sorting, segregating, and processing different types of waste materials. By leveraging AI algorithms and sensor-based technologies, robotic systems can identify and classify various recyclable materials with high accuracy and efficiency, reducing the need for manual labor and minimizing human error (Salem et al., 2023). Moreover, AI-driven robotics can optimize the workflow and throughput of recycling facilities by improving the speed and precision of material handling processes. This increased efficiency translates to higher productivity, lower operational costs, and enhanced overall performance of recycling operations. However, the widespread adoption of AI-driven robotics in waste recycling may have implications for labor-intensive tasks traditionally performed by human workers.

While automation can lead to job displacement in some areas, it also creates new opportunities for skilled workers to oversee and manage robotic systems, perform maintenance tasks, and engage in higher-value activities such as data analysis and process optimization. Additionally, AI-driven robotics can improve workplace safety by reducing workers' exposure to hazardous materials and repetitive strain injuries associated with manual labor (Licardo et al., 2024). Overall, the integration of AI-driven robotics and automation technologies in waste recycling operations promises to revolutionize the industry by increasing efficiency, productivity, and safety while also presenting new challenges and opportunities for the workforce.

In conclusion, integrating AI technologies with existing recycling infrastructure presents several challenges that need to be addressed for successful implementation (Andeobu et al., 2022). One challenge is the compatibility of AI systems with legacy infrastructure and processes, which may require substantial modifications or upgrades to accommodate new technologies. Additionally, the initial investment and operational costs associated with deploying AI solutions can be prohibitive for some recycling facilities, especially smaller operations with limited budgets. Another challenge is ensuring interoperability and data compatibility between different AI systems and existing recycling equipment and databases (Wan et al., 2020). This requires standardized data formats, communication protocols, and integration interfaces to enable seamless data exchange and collaboration across the recycling value chain. Moreover, there may be resistance or skepticism from stakeholders, including facility operators, workers, and regulators, regarding the reliability, accuracy, and safety of AI-driven technologies.

Addressing these challenges requires a coordinated effort involving collaboration between technology developers, recycling facility operators, policymakers, and other stakeholders (Lu et al., 2013). Strategies to mitigate these challenges include providing financial incentives and subsidies to offset implementation costs, offering training and support programs to educate workers on AI technology usage, and developing industry-wide standards and best practices for AI integration in recycling operations. Additionally, fostering an environment of transparency, trust, and collaboration can help build confidence in AI technologies and encourage their widespread adoption across the recycling industry. Continued research, development, and collaboration are essential to overcome challenges, ensure the scalability and cost-effectiveness of AI technologies, and accelerate the transition toward a circular economy (Nižetić et al., 2019).

AI in waste monitoring

Effective waste monitoring is crucial for efficient waste management practices. With the advancements in Artificial Intelligence (AI), waste monitoring has undergone significant transformations, enabling real-time data collection, predictive analytics, data-driven decision-making, and the integration of the Internet of Things (IoT) and sensor networks. Let's explore the current trends and developments in each of these areas:

Real-time monitoring systems

Real-time waste monitoring systems employ AI technologies to collect and analyze data in real time, providing immediate insights into waste generation, collection, and disposal (Ahmed et al., 2022). These systems utilize various sensors, such as ultrasonic sensors, load sensors, and GPS trackers, to capture data on waste levels in bins and containers, collection truck routes, and disposal points. AI algorithms process the data, enabling real-time monitoring and visualization of waste accumulation patterns, optimizing collection schedules, and improving operational efficiency (Salman and Hasar, 2023). The integration of AI with real-time monitoring systems enables proactive response to waste management challenges, such as overflowing bins, irregular collection routes, and optimized resource allocation.

By providing timely information, AI-driven monitoring systems minimize unnecessary truck journeys, optimize resource allocation, and enhance overall operational efficiency (Srinivas et al., 2022). However, implementing such systems at scale poses several technical challenges. One major hurdle is the integration of diverse data sources and sensors into a unified platform, requiring robust infrastructure and interoperability standards (Mounadel et al., 2023). Additionally, ensuring data accuracy, reliability, and security is paramount to the effectiveness of these systems, necessitating stringent data management protocols and privacy safeguards. Moreover, the computational requirements for processing large volumes of data in real-time demand powerful computing resources and efficient algorithms (Akkad et al., 2022; Olawade et al., 2023b). Addressing these technical challenges is crucial to unlocking the full potential of AI-driven monitoring systems in waste management and realizing substantial cost savings and efficiency gains.

Predictive analytics

Predictive analytics utilizes AI algorithms and machine learning techniques to analyze historical and real-time data, enabling the prediction of future waste generation patterns and trends (Bakhshi and Ahmed, 2018; Elshaboury et al., 2021; Erdebilli and Devrim-İçtenbaş, 2022; Garre et al., 2020). By considering factors such as population density, weather conditions, and historical waste data, predictive analytics models can forecast waste generation rates, optimize collection routes, and allocate resources effectively. These models continuously learn from new data, enhancing their accuracy over time. By leveraging predictive analytics, waste management authorities and service providers can proactively plan waste management strategies, optimize collection schedules, and allocate resources efficiently, ultimately reducing costs and improving overall waste management effectiveness (Liao and Wang, 2020).

Also, AI-driven predictive analytics models offer valuable tools for waste management authorities to anticipate and mitigate the impacts of climate change on waste generation patterns and recycling rates (Reza, 2023). By analyzing historical data and environmental factors, these models can forecast changes in waste generation trends, such as fluctuations in consumption patterns and population growth, influenced by climate change (Adeobu et al., 2022). Additionally, predictive analytics can optimize resource allocation and waste management strategies, enabling authorities to adapt to shifting waste streams and prioritize recycling efforts in response to climate-related challenges. For example, predictive models can identify areas prone to increased waste generation during extreme weather events or natural disasters, allowing authorities to implement targeted waste reduction and recovery initiatives. Moreover, AI-powered predictive analytics facilitate proactive decision-making by identifying emerging trends and potential risks (Venigandla et al., 2024). This enables waste management authorities to develop resilient and sustainable strategies to mitigate the impacts of climate change on waste management systems.

Data-driven decision making

AI technologies facilitate data-driven decision-making by analyzing large volumes of data collected from various waste monitoring sources (Ali et al., 2022). AI algorithms process and analyze the data to derive actionable insights and support decision-making in waste management processes (Imran et al., 2020). For example, data on waste generation rates, recycling rates, and disposal costs can help inform policy decisions, infrastructure investments, and resource allocation strategies. AI algorithms can identify trends, correlations, and patterns in the data that may not be readily apparent to human operators, enabling evidence-based decision-making for more efficient and sustainable waste management practices (Nguyen et al., 2022).

IoT and sensor networks

The integration of IoT and sensor networks with AI technologies is revolutionizing waste monitoring (Akram et al., 2021; Pardini et al., 2020; Rahman et al., 2022). IoT devices and sensors are deployed in waste management systems to collect real-time data on various parameters, such as waste levels, temperature, moisture, and air quality. These devices transmit data to centralized platforms, where AI algorithms analyze and process the data to generate meaningful insights (Bernat, 2023; Pardini et al., 2019). IoT and sensor networks enable continuous and comprehensive monitoring of waste generation, collection, and disposal processes (Anjum et al., 2022). They provide a wealth of data that can be utilized for optimizing waste management strategies, improving operational efficiency, and ensuring timely interventions when required (Alqahtani et al., 2020). Moreover, IoT and sensor networks facilitate the integration of multiple waste management systems, enabling seamless data exchange and interoperability (Acharya et al., 2022).

Current trends in AI-driven waste monitoring focus on enhancing the accuracy and reliability of real-time monitoring systems, improving the predictive capabilities of analytics models, leveraging data for informed decision-making, and expanding the integration of IoT and sensor networks (Fayomi et al., 2021; Gull et al., 2021). The goal is to create intelligent waste monitoring systems that enable efficient waste management, reduced environmental impact, and improved resource utilization (Aytaç and Korçak, 2021). Continued research, development, and collaboration among waste management organizations, technology providers, and researchers are essential to drive further advancements in AI-driven waste monitoring and support the transition toward sustainable waste management practices (Namoun et al., 2022).

Challenges and limitations

While Artificial Intelligence (AI) holds immense potential in transforming waste management practices, several challenges and limitations need to be addressed for successful implementation (Aljawder and Al-Karaghouli, 2022; Bui and Tseng, 2022; Vyas et al., 2023; Zhang et al., 2019). Current trends highlight the following key areas of concern:

Data availability and quality

One of the primary challenges in AI-driven waste management is the availability and quality of data (Abunama et al., 2019; Mounadel et al., 2023; Tsui et al., 2023). AI algorithms heavily rely on large and diverse datasets to train and make accurate predictions (Akkad et al., 2022; Alam et al., 2022). However, waste management data may be fragmented, inconsistent, or insufficiently standardized (Yang et al., 2021). Lack of data integration and interoperability among different stakeholders in the waste management ecosystem can hinder the development and deployment of effective AI solutions (Verma, 2023). Furthermore, data collection and monitoring systems need to be robust and reliable to ensure accurate and high-quality data for AI algorithms to yield meaningful insights.

To overcome these challenges, efforts are being made to improve data collection methods and establish data-sharing protocols. Collaborative initiatives between waste management agencies, technology providers, and researchers aim to standardize data formats, develop data platforms, and promote data-sharing practices. Additionally, advancements in IoT and sensor technologies enable the collection of real-time and comprehensive data, enhancing the quality and availability of data for AI-driven waste management applications.

Privacy and security concerns

The implementation of AI technologies in waste management raises privacy and security concerns. AI systems often require access to sensitive data, such as waste generation patterns, collection routes, and user behavior (Edinov and Fauzi, 2023; Farjami et al., 2020). Protecting the privacy and security of this data is crucial to maintain public trust and compliance with data protection regulations. There is a need to balance the benefits of AI-driven waste management with privacy considerations (Abioye et al., 2021). To address these concerns, privacy-enhancing techniques such as data anonymization and encryption are being employed. Additionally, regulatory frameworks are evolving to ensure responsible data handling practices and to protect individual privacy rights. Striking the right balance between data accessibility for AI algorithms and ensuring data privacy and security is a critical challenge that needs ongoing attention.

Furthermore, another major concern is the collection and storage of personal information, such as household waste generation data, which raises privacy issues regarding data ownership, consent, and unauthorized access (Farjami et al., 2020). Additionally, the integration of IoT devices and sensor networks in waste management systems increases the risk of cyberattacks and data breaches, potentially compromising the confidentiality and availability of data (Habibzadeh et al., 2019). To effectively mitigate these concerns without compromising the effectiveness of AI systems, robust data protection measures and security protocols must be implemented. This includes encrypting sensitive data, implementing access controls and authentication mechanisms, and regularly updating software and firmware to patch vulnerabilities. Moreover, transparent data governance frameworks and privacy policies should be established to clarify how data is collected, processed, and shared, while providing individuals with control over their personal information (Habibzadeh et al., 2019; Abioye et al., 2021). By prioritizing privacy and security measures in the design and deployment of AI systems, waste management authorities can foster trust among stakeholders and ensure the responsible and ethical use of AI technologies in waste management practices.

To address privacy concerns and ensure data security in AI-driven waste management systems, several recommendations can be implemented. Firstly, adopting encryption techniques to protect sensitive data during storage and transmission can enhance data security. Additionally, implementing access controls and user authentication mechanisms can restrict unauthorized access to data. Regular security audits and vulnerability assessments are essential to identify and mitigate potential security threats proactively. Moreover, ensuring compliance with relevant data protection regulations such as General Data Protection Regulation (GDPR) and Health Insurance Portability and Accountability Act (HIPAA) is crucial to safeguarding user privacy. Lastly, promoting transparency and accountability in data handling practices by providing clear information to users about how their data is collected, processed, and used can enhance trust and confidence in AI-driven waste management systems.

Cost and infrastructure requirements

The implementation of AI technologies in waste management may involve significant upfront costs and infrastructure requirements (Bhubalan et al., 2022; Borchard et al., 2022). AI systems often require specialized hardware, software, and computational resources to handle large datasets and complex algorithms. Additionally, integrating AI technologies with existing waste management infrastructure can pose challenges in terms of compatibility, scalability, and cost-effectiveness. To overcome these challenges, there is a need for cost-effective AI solutions that can be easily integrated into existing waste management systems (Chen et al., 2022; Dimri et al., 2020; Negreiros Gomes et al., 2023). Cloud computing and edge computing technologies provide scalable and cost-efficient options for deploying AI algorithms and managing computational demands (Janbi et al., 2020; Thalluri et al., 2021; C. Wang et al., 2021; Zingg et al., 2021). Collaborative efforts between technology providers, waste management agencies, and policymakers can help identify strategies to reduce implementation costs and streamline infrastructure requirements.

Ethical considerations

The adoption of AI technologies in waste management introduces potential biases and ethical considerations that necessitate careful attention (Al-Sharafi et al., 2023). One significant concern revolves around the potential biases introduced by AI algorithms during decision-making processes, which could inadvertently perpetuate disparities or yield unintended outcomes. This issue is particularly pertinent in waste management, where equitable resource allocation and fair treatment of communities are paramount. To mitigate biases, transparency, explainability, and accountability are essential pillars in AI-driven systems (Al-Ruzouq et al., 2022).

Efforts are underway to develop algorithms that offer transparency and explainability, enabling stakeholders to understand the rationale behind AI-driven decisions. This transparency empowers stakeholders to scrutinize decision-making processes and identify and rectify biases as necessary. Moreover, ethical guidelines and frameworks are being established to govern the responsible use of AI in waste management (Brendel et al., 2021). These frameworks advocate for fairness, equity, and inclusivity in AI deployment, ensuring that algorithms operate within ethical boundaries. By adhering to transparent practices and ethical guidelines, the waste management sector can uphold principles of fairness and transparency while harnessing the potential of AI to optimize waste management processes. Ongoing research and collaboration are crucial to further refine AI algorithms and develop robust ethical frameworks that safeguard against biases and promote equitable outcomes in waste management decision-making.

Future directions and opportunities

The integration of Artificial Intelligence (AI) in waste management has shown significant promise in improving efficiency, sustainability, and resource optimization (Ihsanullah et al., 2022). As the field continues to evolve, several future directions and opportunities are emerging. Current trends highlight the following key areas of focus:

Integration of AI and Internet of Things (IoT)

The integration of AI with the Internet of Things (IoT) and Internet of Vehicles (IoV) is expected to play a pivotal role in the future of waste management (Baddegama et al., 2022; Ijemaru et al., 2023). IoT devices, such as sensors, actuators, and smart bins, generate vast amounts of real-time data that can be leveraged by AI algorithms for decision-making and optimization (Martikkala et al., 2023). The synergy between AI and IoT enables the creation of intelligent waste management systems that can autonomously monitor, analyze, and optimize waste collection, sorting, recycling, and disposal processes (Mousavi et al., 2023). This integration will enable smarter waste management operations, predictive maintenance of waste management infrastructure, and improved real-time monitoring and control.

Advancements in machine learning and deep learning

Machine learning (ML) and deep learning (DL) algorithms are at the forefront of AI advancements and are expected to continue evolving in the context of waste management (Munir et al., 2023). ML algorithms, such as decision trees, random forests, and support vector machines, are being enhanced to improve waste classification, sorting, and predictive modeling capabilities (Adeleke et al., 2023; Srinilta and Kanharattanachai, 2019). DL algorithms, particularly convolutional neural networks (CNNs) and recurrent neural networks (RNNs) are revolutionizing waste image recognition, material identification, and quality control processes (Ba Alawi et al., 2021; Li et al., 2021). The future will witness advancements in ML and DL algorithms that can handle complex waste streams, adapt to dynamic waste management scenarios, and leverage large-scale data for improved decision-making and optimization (Oruganti et al., 2023).

Collaboration and knowledge sharing

Achieving seamless integration and collaboration among different stakeholders in the recycling value chain faces several key barriers that hinder progress. One significant challenge is the lack of standardized data formats and interoperable systems, which impede the seamless exchange of information between waste management companies, technology providers, researchers, and policymakers (Heikkilä et al., 2023). Additionally, concerns regarding data privacy, ownership, and security often discourage stakeholders from sharing valuable data and insights (Amirsoleymani et al., 2022). Moreover, the absence of centralized platforms for data sharing and knowledge exchange further exacerbates fragmentation within the recycling value chain (Kolditz et al., 2023).

However, AI-driven platforms offer promising solutions to overcome these barriers. By leveraging advanced algorithms and data analytics capabilities, these platforms can facilitate secure and efficient data sharing while ensuring privacy and compliance with regulatory requirements. Open-source projects and knowledge-sharing platforms play a crucial role in fostering collaboration and innovation by providing accessible frameworks and tools for stakeholders to collaborate and co-create solutions (Heikkilä et al., 2023). By embracing AI-driven platforms for data sharing and knowledge exchange, stakeholders can harness collective intelligence, accelerate the development of innovative waste management solutions, and drive continuous improvement across the recycling value chain.

Collaboration among stakeholders, including waste management agencies, technology providers, and policymakers, is crucial for the responsible adoption of AI in waste management (Kurniawan et al., 2024). Waste management agencies can provide valuable insights into the specific challenges and needs of the industry, while technology providers can offer innovative solutions leveraging AI. Policymakers play a pivotal role in creating an enabling regulatory environment that promotes the ethical and sustainable use of AI in waste management. By working together, stakeholders can share expertise, resources, and best practices, fostering innovation and driving positive outcomes for both the environment and society (Zhang et al., 2019). This collaboration can lead to the development of tailored AI solutions that address the unique requirements of waste management while ensuring compliance with regulations and ethical standards. Additionally, it can facilitate the implementation of transparent and accountable AI systems, promoting trust and acceptance among the public. Ultimately, collaboration among stakeholders can accelerate the adoption of AI in waste management, leading to more efficient, sustainable, and environmentally friendly practices.

Policy and regulatory frameworks

Developing regulatory frameworks and industry standards is essential to ensure the responsible and ethical use of AI in waste management. These frameworks should address key concerns such as data privacy, security, fairness, and transparency. Policy initiatives can play a crucial role in promoting data sharing, incentivizing AI adoption, and fostering interoperability (Naveenkumar et al., 2023). Additionally, regulatory frameworks can provide guidelines for responsible waste management practices, ensuring that AI algorithms prioritize environmental sustainability and social equity (Andeobu et al., 2022). Governments and regulatory bodies have a central role in shaping these frameworks, as they can create an enabling environment that supports innovation while safeguarding public interests (Singh et al., 2022). By collaborating with industry stakeholders, policymakers can develop regulations that balance the need for innovation with the protection of ethical principles and societal values.

Furthermore, emerging opportunities in AI-driven waste management include the application of natural language processing (NLP) for waste data analysis, AI-powered robotics for waste sorting and processing, and AI-driven optimization techniques for waste transportation and logistics (John and Oloruntoba, 2020). These technologies have the potential to revolutionize waste management by improving efficiency, reducing operational costs, and minimizing environmental impact. However, their widespread adoption requires careful consideration of ethical, regulatory, and technical challenges. Regulatory frameworks should adapt to the evolving landscape of AI technologies, ensuring that they promote innovation while safeguarding public welfare and environmental sustainability. As AI continues to advance, governments and regulatory bodies must remain proactive in updating policies and standards to address emerging risks and opportunities in AI-driven waste management.

Conclusion

Despite the remarkable advancements and benefits, challenges related to data availability, privacy, cost, infrastructure, and ethics need to be addressed collaboratively by stakeholders including waste management agencies, technology providers, researchers, and policymakers. The recommendations below can help to further foster the responsible and sustainable utilization of AI in this field;

I. Data Accessibility and Quality Improvement: Efforts should be made to ensure the availability and accuracy of data, which is the foundation of AI-driven solutions. Waste management authorities and technology developers should collaborate to collect, share, and maintain high-quality waste-related data to enable accurate predictions and informed decision-making.

II. Privacy and Security Considerations: As AI systems rely on data, it is crucial to address privacy concerns associated with data collection, processing, and storage. Implementing robust data security measures, adhering to data protection regulations, and anonymizing sensitive information can help build trust among stakeholders.

III. Investment in AI Infrastructure: Governments, waste management agencies, and organizations should invest in the necessary infrastructure to support AI-driven waste management solutions. This includes the deployment of smart sensors, IoT devices, and connectivity technologies to facilitate real-time data collection and communication.

IV. Research and Innovation: Continued research and innovation are essential to keep up with the rapid advancements in AI technologies. Collaboration between academia, industry, and governments can lead to the development of novel AI algorithms, models, and applications tailored to specific waste management challenges.

V. Capacity Building and Training: Training programs and capacity-building initiatives should be offered to waste management professionals to enhance their understanding of AI technologies. This will enable them to effectively integrate and manage AI solutions in waste collection, sorting, recycling, and monitoring processes.

VI. Ethical and Social Considerations: Ethical implications related to AI in waste management, such as job displacement, environmental justice, and community engagement, need to be addressed. Multidisciplinary discussions involving ethicists, policymakers, community representatives, and industry experts can lead to responsible AI adoption.

VII. Pilot Projects and Demonstrations: Governments and organizations can initiate pilot projects and demonstrations to showcase the feasibility and benefits of AI-driven waste management solutions. These projects can help build public awareness, gather real-world data, and assess the economic and environmental impacts.

VIII. Regulation and Standards: Regulatory frameworks and industry standards for AI applications in waste management should be developed to ensure responsible and safe implementation. These regulations can guide the development, deployment, and operation of AI technologies while addressing potential risks.

CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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