Next-Generation Computing Systems and Technologies
http://dx.doi.org/10.62762/NGCST.2026.790821

REVIEW ARTICLE

# Waste Management and Circular Economy: A Comprehensive Review of AIoT Applications in Intelligent Waste Sorting, Data Analytics for Resource Recovery, and Sustainable Infrastructure Development

**Snehal Panda**[1,*], **Atanu Jana**[1], **Manoswini Nahak**[2], **G. Singaravel**[3], **Sandipan Mallik**[1] **and Kunjabihari Swain**[4]

[1] Department of Electronics and Communication Engineering, NIST University, Berhampur, Odisha 761008, India
[2] Department of Computer Science and Engineering, NIST University, Odisha 761008, India
[3] Department of Information Technology, KSR College of Engineering, Tamil Nadu 637215, India
[4] Department of Electrical Engineering, NIST University, Odisha 761008, India

## Abstract

**Artificial Intelligence of Things (AIoT) is transforming linear waste management into intelligent, data-driven solutions that support circular economy (CE) principles. This narrative review synthesizes peer-reviewed studies from 2020–2025 on AIoT applications across intelligent waste sorting, data analytics for resource recovery, and sustainable infrastructure development. The review examines IoT-enabled smart bins, computer-vision robotic sorting, machine learning classifiers (VGG-16/19: 97.11–99.7% accuracy, ResNet: 91.5–98.16%), predictive analytics, and graph-based route optimization. Reported improvements include up to 50% reduction in overflow events, 15.5–30% fuel savings, and 35.5% better bin utilization. These technologies enhance material recovery, reduce landfilling, and support closed-loop resource flows. Challenges—including high costs, data privacy, and limited model generalizability—are discussed alongside future directions such as edge-AI, blockchain, and multi-modal sensing. AIoT shows strong potential to advance UN SDGs 11 and 12, offering a roadmap for scalable urban circular economy transitions.**

**Keywords**: AIoT, circular economy, intelligent waste sorting, resource recovery, sustainable infrastructure, smart waste management, predictive analytics.

## 1 Introduction

Every year, municipalities all around the world generate over 2.01 billion tonnes of municipal solid waste, which will reach or exceed 70% growth by 2050. This rapid increase in waste generation threatens traditional linear "take-make-dispose" processes and

**Submitted:** 14 April 2026
**Accepted:** 15 June 2026
**Published:** 30 June 2026

**Vol.** 2, **No.** 2, 2026.
10.62762/NGCST.2026.790821

***Corresponding author:**
✉Snehal Panda
snehalpanda06@gmail.com

**Citation**
Panda, S., Jana, A., Nahak, M., Singaravel, G., Mallik, S., & Swain, K. (2026). Waste Management and Circular Economy: A Comprehensive Review of AIoT Applications in Intelligent Waste Sorting, Data Analytics for Resource Recovery, and Sustainable Infrastructure Development. *Next-Generation Computing Systems and Technologies*, 2(2), 64–69.

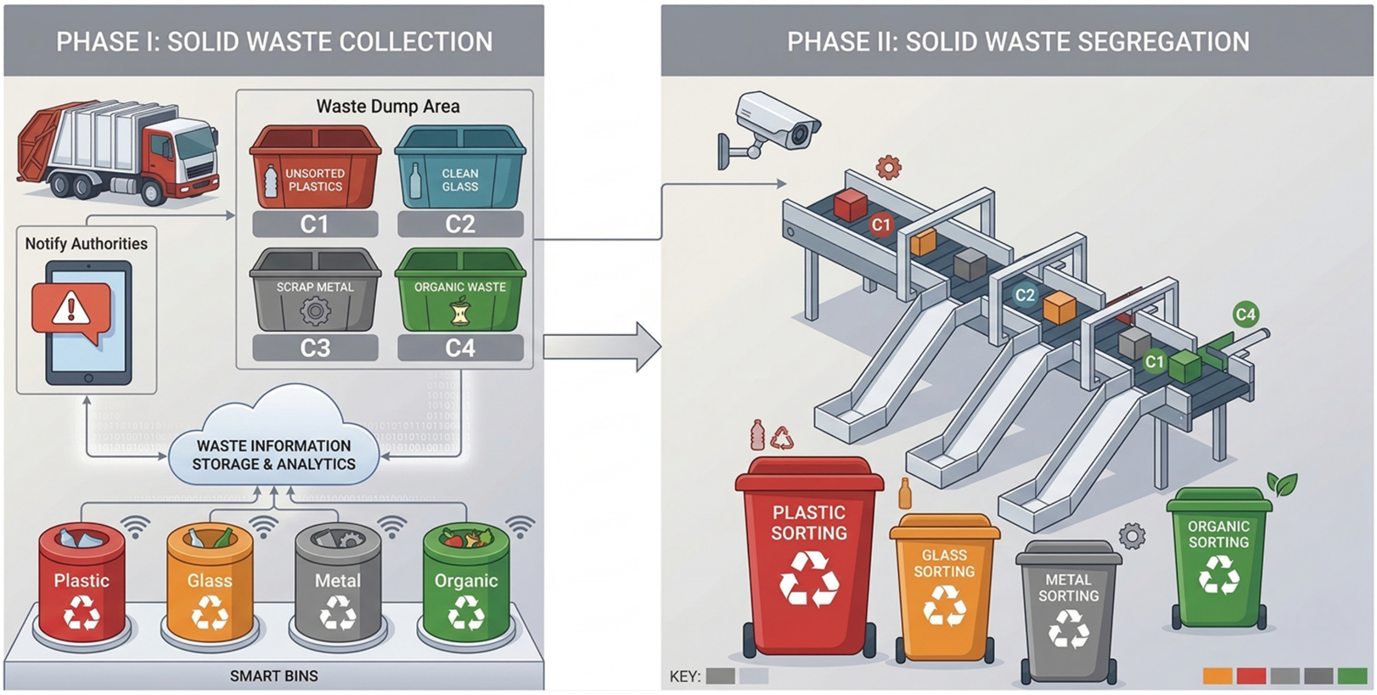

**Figure 1.** Architecture of an AIoT-enabled smart waste collection and segregation system.

further exacerbates environmental degradation [1]. A possible solution to these two major challenges is to implement a circular economy that emphasizes reduce, reuse, recycle, and recover. However, to implement a circular economy effectively requires real-time monitoring, automated decision-making, and optimized logistics. To achieve this synergy between real-time monitoring, automation, and optimization, AIoT combines low-power IoT-type sensors with cloud and edge-based AI algorithms [2, 3].

This paper reviews three primary interrelated components; (1) intelligent waste sorting using computer vision and robotics, (2) data analytics for predicting resource recovery, and (3) AIoT-driven sustainable infrastructure. The document synthesizes empirical evidence from new research papers and focuses on quantifiable benefits while relying on publication-supplied metrics. The review focuses on urban municipal solid waste systems. Ultimately, this paper evaluates AIoT's ability to contribute to the broader movement towards large scale implementation of circular economy systems.

## 2 Fundamentals of AIoT in Waste Management

Low-power IoT devices, such as ultrasonic (HC-SR04), load cell (weight), MQ-series (gas), and RFID sensors, are integrated with machine learning algorithms such as CNNs and XGBoost. Communication relies on low-power wide-area protocols like LoRaWAN (868/915 MHz, long-range) and NB-IoT. Smart bins transmit real-time fill-level, composition estimates, and geolocation data to cloud platforms, enabling dynamic analytics. Edge computing on microcontrollers (e.g., ESP32 with TensorFlow Lite or Raspberry Pi) minimizes latency for on-site classification and actuation [4]. This convergence of low-latency edge intelligence with IoT sensing reflects a broader reconceptualization of AIoT as a foundational enabler of circular economy transitions [5].

The multi-layered architecture designed for AIoT provides the support for achieving circular economy goals, diverting recyclables from the source, reducing the contamination of recyclables, and creating the means for traceability through potential integration of Blockchain [3]. The overall system architecture, illustrating the integration of IoT sensing, edge computing, cloud analytics, and actuation modules, is depicted in Figure 1.

## 3 Intelligent Waste Sorting with AIoT

### 3.1 Sensor and Computer-Vision Technologies

IoT-enabled bins employ ultrasonic and load-cell sensors for continuous real-time capacity monitoring (typically ±1–2 cm accuracy). Material classification occurs via RGB cameras (often 1080p resolution) mounted on conveyor belts. Data transmission uses LoRaWAN, offering long-range (up to 10–15 km in

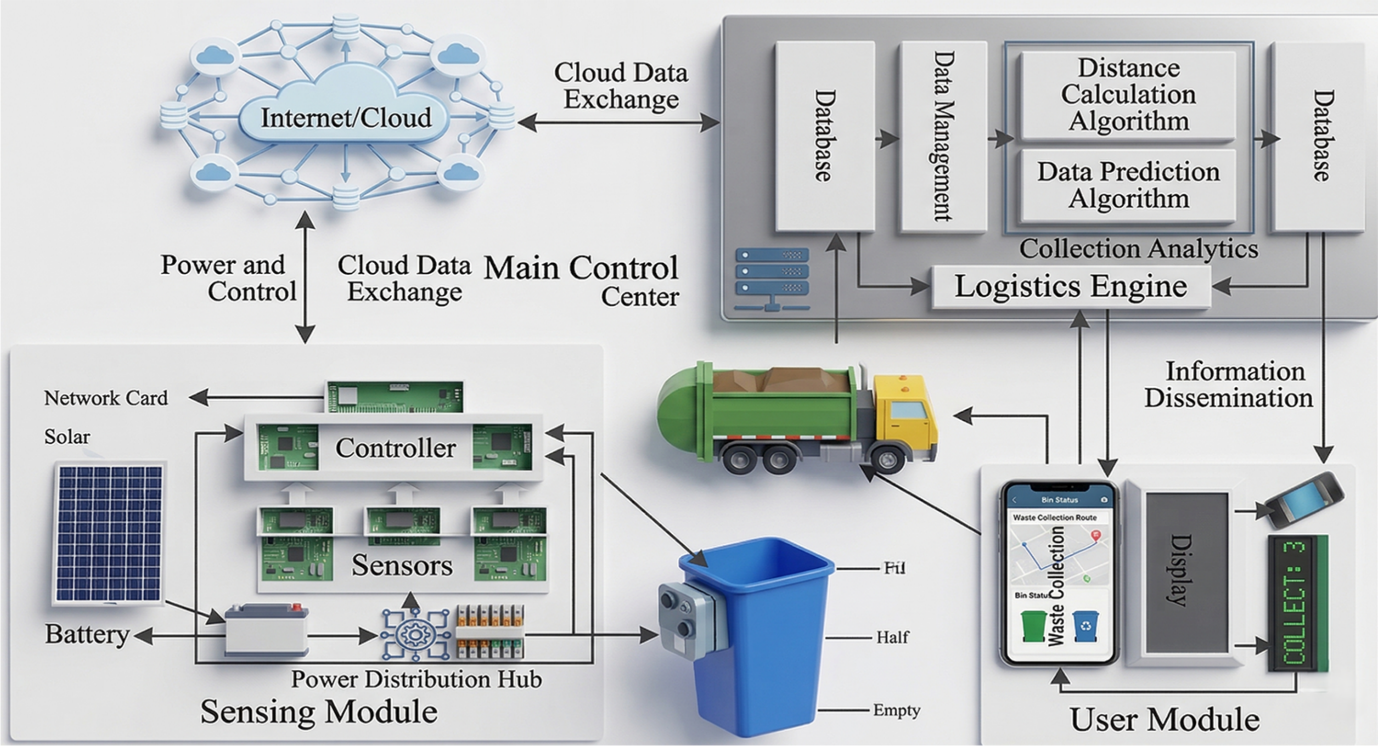

**Figure 2.** IoT sensing module for smart waste bins and user interface for fill-level monitoring.

urban areas) and low-power connectivity [4, 9]. A typical IoT sensing module for smart waste bins, along with a user interface for real-time fill-level monitoring, is illustrated in Figure 2.

## 4 Deep-Learning Classifiers and Robotic Systems

Transfer-learning models have shown effectiveness in handling heterogeneous waste streams. VGG-16 and VGG-19 architectures pretrained on datasets such as TrashNet have achieved validation accuracies ranging from 97.11% to 99.7% when deployed with Raspberry Pi-based actuators for classifying plastics, glass, metals, and other materials [6, 7]. ResNet-based models have classified into up to 12 waste categories (organic, recyclable, hazardous) with reported accuracies of 91.5%–98.16% after data augmentation and hyperparameter tuning using the Adam optimizer (learning rate 0.001, 150 epochs) [6]. Figure 3 presents an AI-powered robotic waste sorting system, while Figure 4 illustrates the conveyor-belt computer-vision architecture for automated material classification.

Robotic arm systems guided by computer vision have demonstrated material purity rates exceeding 95% (and up to 99–100% for specific streams such as HDPE) in material recovery facilities, offering 10–12% higher target material recovery compared with manual sorting [8].

Case studies have shown that robotic arm systems can yield an additional 20% to 30% in material recovery rates along with a 25% to 35% reduction in cost compared with traditional manual sorting methods [10, 11]. A comparative summary of key AI models and their performance metrics in waste management applications is presented in Table 1.

## 5 Data Analytics for Resource Recovery

Large volumes of IoT-generated data—including volume, composition, and GPS location—can be used to power predictive models to optimize resource recovery. For example, the use of XGBoost classifiers can predict the potential for bin overflows with

**Table 1.** Comparison of AI models in waste management applications.

| Model | Application | Accuracy (%) | Key Metric | Benefit(vs.Baseline) | Source |
|---|---|---|---|---|---|
| VGG-16/19 | Material classification | 97.11–99.7 | Validation/training accuracy | High recall for recyclables | [6, 7] |
| ResNet | Multi-category sorting | 91.5–98.16 | Precision ~97–98% | Reduced contamination | [6] |
| XGBoost | Overflow prediction | 94.1 | Recall 95.8%, AUC high | Up to 50% fewer overflows | [2] |
| CNN + Robotics | Automated sorting | 91–100 | Material purity | 10–30% higher recovery | [8] |

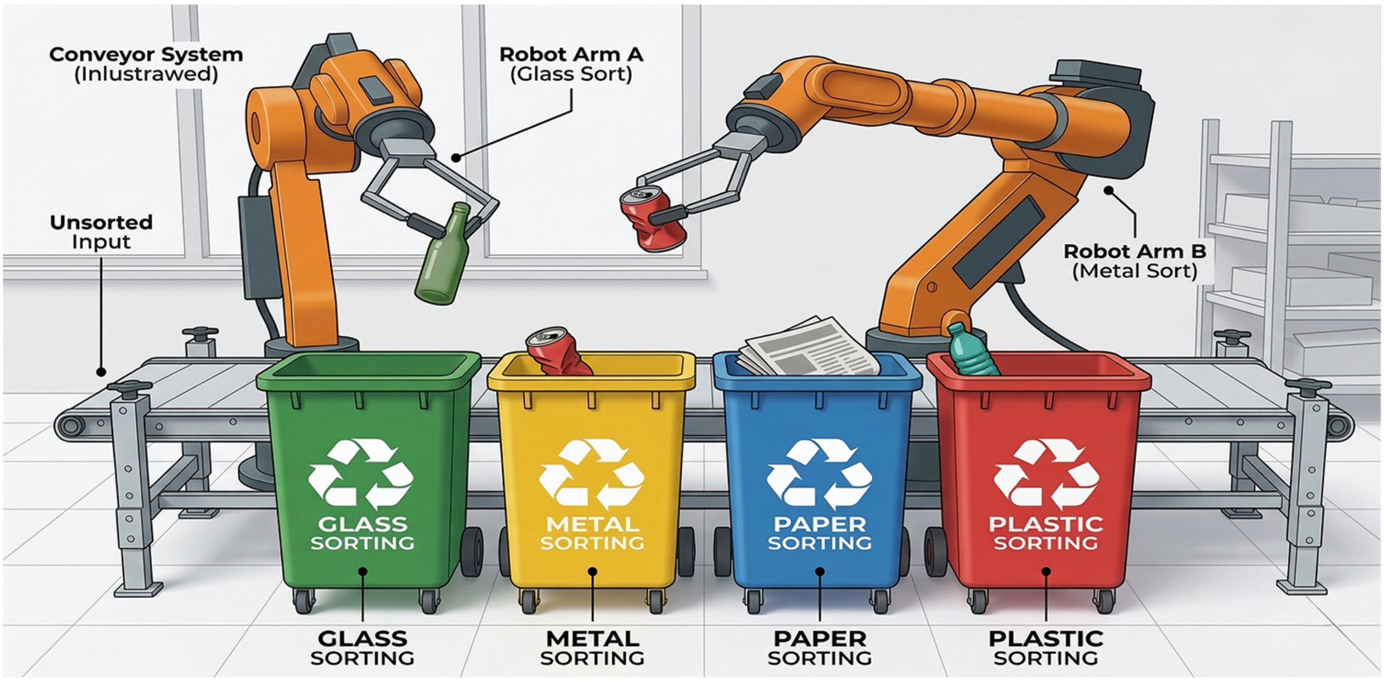

**Figure 3.** AI-powered robotic waste sorting system.

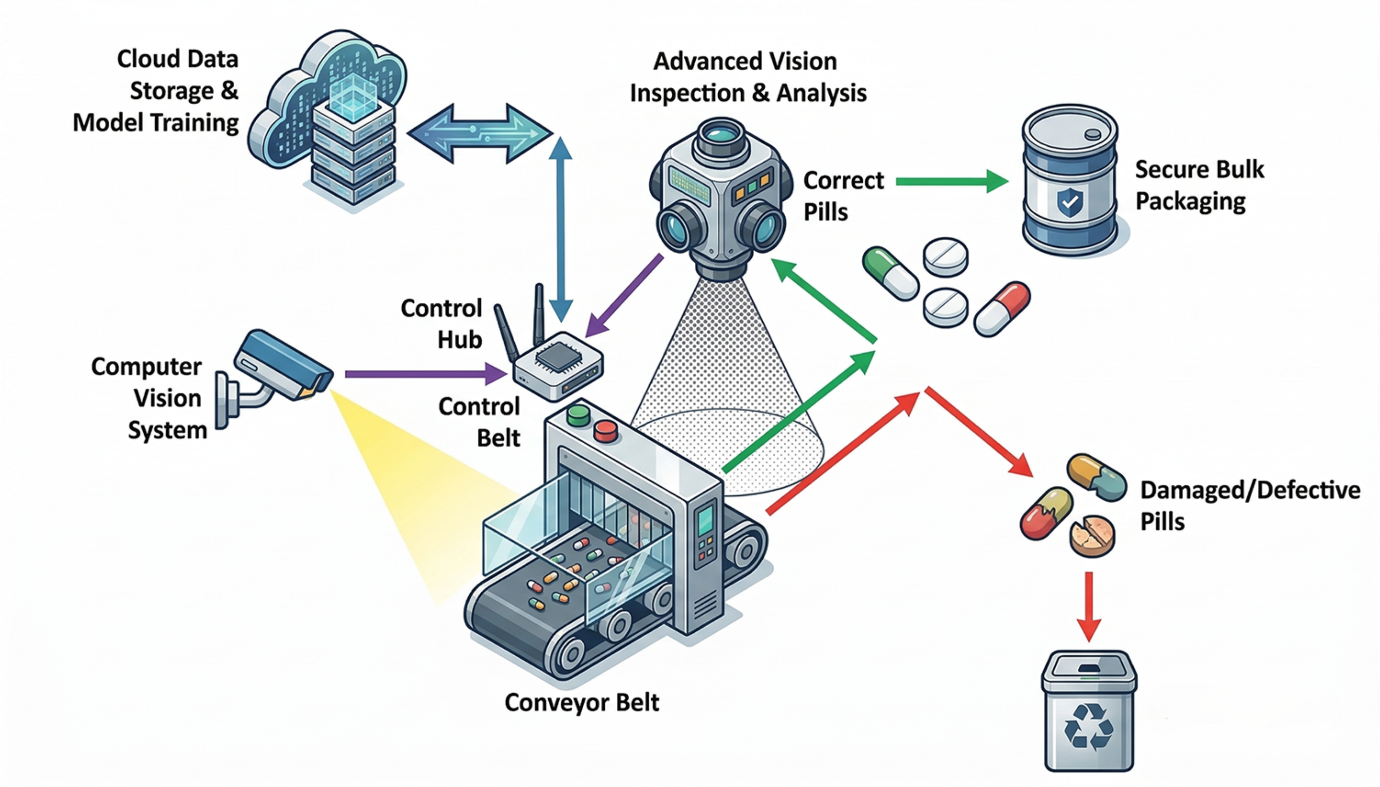

**Figure 4.** Conveyor-belt computer-vision architecture for automated sorting.

94.1% accuracy, 95.8% recall, and strong AUC-ROC performance which can allow for the timely diversion of organics to composting and recyclables to processing facilities [2].

Graph theoretic routing applied to weighted bin networks yields a 15.5% reduction in fuel consumption; a 50% reduction in the occurrence of overflow events; a 72.7% reduction in missed pickups; and a 35.5% increase in the utilization of bins when compared with static collection schedules [2, 12].

Predictive analytics can also be used to identify high-value material streams such as e-waste and

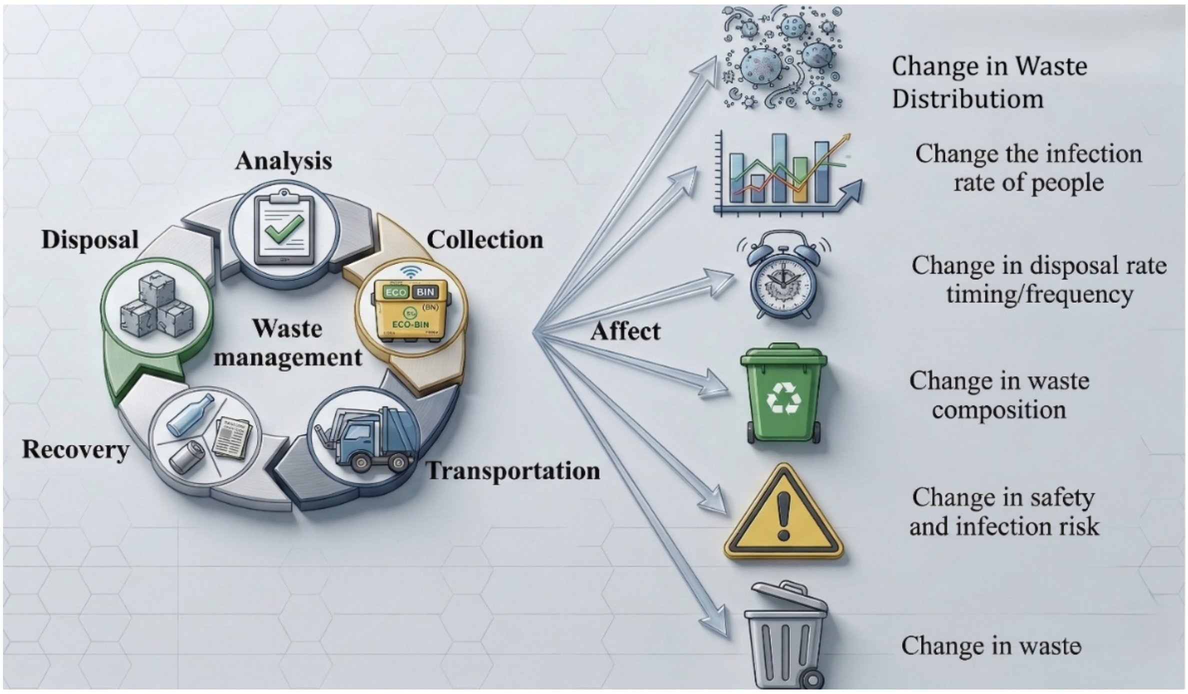

**Figure 5.** Circular economy framework for waste management.

certain types of plastics and to create targeted recovery programs that will reduce demand for virgin materials [1, 3].

## 6 Sustainable Infrastructure Development

AIoT is enabling the development of smart-city infrastructure through optimized collection fleets, modular material recovery facilities, and the application of citizen incentives. The combination of dynamic collection routing and predictive maintenance can extend the useful life of assets, and Blockchain technology can provide end-to-end traceability of the materials from the bin to the final recycled product [3, 13]. A circular economy framework for waste management, integrating AIoT-enabled collection, sorting, recovery, and recycling loops, is shown in Figure 5.

Bin utilization rates showed an improvement of 35.5% due to the installation of GIS (Geographic Information System) integrated zone-specific diversion strategies (e.g., diverting organics into compost and textiles for upcycling), which advance circular economy loops and align with relevant UN Sustainable Development Goals (SDGs) [2, 12].

## 7 Challenges, Opportunities, and Future Directions

Implementing these systems faces multiple challenges, including high capital costs, sensor reliability concerns in extreme weather conditions, compliance with data privacy regulations (e.g., GDPR), bias created from using imbalanced datasets to train models, and potential labor market implications of autonomous systems [1, 10]. There are several potential opportunities for developing low latency decision-making with edge-AI, Privacy-preserving federated learning for training models, multi-spectral and hyper-spectral imaging for finer granularity when identifying materials, blockchain-IoT hybrid solutions for providing transparent global waste tracking [3, 13].

Future research priorities should include the development of standardized open downloadable waste data sets, implementing Explainable Artificial Intelligence (XAI) to provide evidence of compliance with regulatory approvals, completing Lifecycle Assessments (LCA) of AIoT systems from a carbon footprint perspective, and developing Hybrid Biological-Digital Applications (e.g., AI-guided enzymatic processes using real-time composition data). Decentralized AI and Reinforcement Learning for adaptive networks within Circular Economies represent particularly compelling areas of research, as autonomous sorting and recycling systems continue to evolve toward greater operational independence [8], building on the growing emphasis on explainable and trustworthy AI models for regulatory compliance in waste prediction systems [14].

## 8 Conclusion

AIoT technologies show considerable promise in advancing circular economy objectives through intelligent sorting accuracies reported between 97% and 99.7%, predictive resource recovery that can reduce overflow events by up to 50%, and infrastructure efficiency gains ranging from 15% to 35%. Real-world implementations have demonstrated measurable environmental, economic, and social benefits. Collaboration among policymakers, municipalities, and researchers on scalable pilot programs, ethical frameworks, and open standards will be essential for widespread adoption. This review provides symposium participants with a technically grounded foundation to develop innovative solutions that close material loops and promote regenerative urban systems.

## Data Availability Statement

Not applicable.

## Funding

This work was supported without any funding.

## Conflicts of Interest

The authors declare no conflicts of interest.

## AI Use Statement

The authors declare that Grok-4.1 was used for drafting assistance, grammar correction, and sentence-level language improvement. The authors have carefully reviewed, revised, and verified the AI-assisted content and take full responsibility for the final manuscript.

## Ethical Approval and Consent to Participate

Not applicable.

## References

[1] Lakhouit, A. (2025). Revolutionizing urban solid waste management with AI and IoT: A review of smart solutions for waste collection, sorting, and recycling. *Results in Engineering*, *25*, 104018. [CrossRef]

[2] Anitha, R., & Parthiban, A. (2025). AI-IoT-graph synergy for smart waste management: a scalable framework for predictive, resilient, and sustainable urban systems. *Frontiers in Sustainability*, *6*, 1675021. [CrossRef]

[3] Olawade, D. B., Fapohunda, O., Wada, O. Z., Usman, S. O., Ige, A. O., Ajisafe, O., & Oladapo, B. I. (2024). Smart waste management: A paradigm shift enabled by artificial intelligence. *Waste Management Bulletin*, *2*(2), 244-263. [CrossRef]

[4] Baldo, D., Miozzo, M., Giusto, D., & Ghibaudi, M. (2021). A multi-layer LoRaWAN infrastructure for smart waste management. *Sensors*, *21*(8), Article 2600. [CrossRef]

[5] Lampropoulos, G., Rahanu, H., Georgiadou, E., Siakas, D., & Siakas, K. (2024). Reconsidering a sustainable future through artificial intelligence of things (AIoT) in the context of circular economy. In *Artificial Intelligence of Things for Achieving Sustainable Development Goals* (pp. 1-20). Cham: Springer Nature Switzerland. [CrossRef]

[6] Ahmad, G., Aleem, F. M., Alyas, T., Abbas, Q., Nawaz, W., Ghazal, T. M., ... & Ibrahim, A. M. (2025). Intelligent waste sorting for urban sustainability using deep learning. *Scientific reports*, *15*(1), 27078. [CrossRef]

[7] Alourani, A., Ashraf, M. U., & Aloraini, M. (2025). Smart waste management and classification system using advanced IoT and AI technologies. *PeerJ Computer Science*, *11*, e2777. [CrossRef]

[8] Bernat, K. (2023). Post-consumer plastic waste management: from collection and sortation to mechanical recycling. *Energies*, *16*(8), 3504. [CrossRef]

[9] Daas, A., Sari, B., Semchedine, F., & Amad, M. (2025). Optimizing waste management with integrated AIoT, edge computing, and LoRaWAN communication technologies. *Internet of Things*, *31*, 101546. [CrossRef]

[10] Fang, B., Yu, J., Chen, Z., Osman, A. I., Farghali, M., Ihara, I., ... & Yap, P. S. (2023). Artificial intelligence for waste management in smart cities: a review. *Environmental Chemistry Letters*, *21*(4), 1959-1989. [CrossRef]

[11] Lubongo, C., Bin Daej, M. A., & Alexandridis, P. (2024). Recent developments in technology for sorting plastic for recycling: The emergence of artificial intelligence and the rise of the robots. *Recycling*, *9*(4), 59. [CrossRef]

[12] Gouskir, L., Abouhilal, A., Gouskir, M., Baslam, M., Belhouideg, S., & Hachimi, H. (2026). Revolutionizing urban waste systems: A comprehensive review of IoT, AI, and optimization techniques for smart waste management. *International Journal of Advanced Computer Science and Applications*, *17*(5). [CrossRef]

[13] Sánchez-García, E., Martínez-Falcó, J., Marco-Lajara, B., & Manresa-Marhuenda, E. (2024). Revolutionizing the circular economy through new technologies: A new era of sustainable progress. *Environmental Technology & Innovation*, *33*, 103509. [CrossRef]

[14] Adeleke, O., & Jen, T. C. (2025). Explainable AI and machine learning-based analysis of municipal solid waste generation rate: a South African case study. *Waste Management*, *206*, 115036. [CrossRef]