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Review:

A Review on "Solid Waste Management by Using IoT and AI"

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Abstract:

This systematic review emphasis on current research, applications, and challenges in deploying IoT and AI technologies for optimizing waste collection, sorting, recycling, and disposal.The study systematically reviews the integration of 'Internet of Things' (IoT) and 'Artificial Intelligence' (AI) in global waste management, with a focused on a South Korea as anexample of best practices in waste management. South Korea's IoT- and AI-driven systemfeaturing 'Smart Garbage Bins' (SGBs),'RFID-based Pay-As-You-Throw' (PAYT), and 'Dynamic routing algorithms'—is compared with systems in the European Union, United States, and Japan. The study concludes that successful waste digitalization depends on 'Technology integration, Legislative support, and Public engagement', offering a replicable model for nations transitioning toward a circular economy.

Keywords: IoT, AI, Smart Waste Management, PRISMA, Comparative Analysis, Circular Economy, South Korea, PAYT

1. Introduction

The rising volume of global waste demands innovative, technology-driven management solutions. Countries worldwide are experimenting with IoT, AI, and automation to improve waste collection, sorting, and recycling efficiency. The exponential growth of global waste generation, driven by urbanization and consumption patterns, presents a critical environmental and operational challenge for municipalities and industries worldwide (2). Traditional waste management systems, often characterized by stationary schedules, inefficient routing, and low recycling rates, are increasingly inadequate, leading to escalating costs, environmental pollution, and public health concerns. In response, the integration of Internet of Things (IoT) and Artificial Intelligence (AI) has emerged as a transformative model for developing smart, data-driven waste management.

This systematic review emphasis contemporary research on the convergence of IoT and AI in waste management. IoT technologies, through networks of sensors and connected devices, enable the real-time monitoring of waste bin fill-levels, environmental conditions, and asset locations. AI, particularly machine learning and computer vision, controls this data stream to introduce predictive analytics, intelligent automation, and optimized decision-making.

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Together, they facilitate applications ranging from dynamic collection routing and automated waste sorting to predictive maintenance of facilities and enhanced recycling chain transparency(4).

By critically examining the technological architectures, demonstrated benefits, and persistent challenges documented in recent literature, this review aims to provide a comprehensive overview of the state-of-the-art. It highlights how the interaction of IoT and AI is foundational to advancing toward efficient, sustainable, and circular waste management systems.South Korea has emerged as a benchmark, integrating these technologies within a supportive policy framework to achieve a circular economy(5).

Multiple studies highlight the use of ultrasonic sensors, microcontrollers (e.g., Arduino Uno), and wireless communication (GSM, LoRaWAN) to monitor bin fill levels in real-time.

- Sohag & Podder (2020) developed an integrated system with automated lids, LCD displays, and GSM-based alerts to optimize collection routes and prevent overflow.
- Lundin et al. (2017) emphasized low-cost, retrofittable sensors (under $100 per bin) using LoRaWAN for long-range, low-power communication. Their user-centred design involved stakeholders to ensure practicality and scalability.
- Farooq et al. (2022) reviewed companies like Bigbelly, Enevo, and Sensoneo, which offer smart compaction, route optimization, and data analytics to improve operational efficiency.

2. Research Methodology:

Conducted the systematic review following the ‘PRISMA 2020 guidelines’ to identify, select, and analyse studies on IoT and AI in waste management.

2.1 Identification

Databases Searched: Scopus, Web of Science, IEEE Xplore, ScienceDirect, and Google Scholar.

Search Terms: (‘IoT’ OR ‘Internet of Things’) AND (‘AI’ OR ‘Artificial Intelligence’) AND (‘waste management’ OR ‘smart waste management techniques’) AND (‘case study’ OR ‘South Korea’).

Time Frame: 2015–2024.

Initial Records Identified:1,248 studies.

2.2 Screening:

Duplicates Removed

Title and Abstract Screening

Full-Text Assessed for Eligibility

Excluded After Full-Text Review

Studies Included in Qualitative Synthesis

2.3 Data Extraction and Synthesis:

Data were extracted into a standardized matrix covering:

Technology type (IoT, AI, robotics)

Policy framework

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Key performance indicators (KPIs)

3. Integration of IoT and AI

These sources examine the integration of artificial intelligence (AI), machine learning, and the Internet of Things (IoT) to modernize global waste management. Researchers highlight how smart sensors and automated sorting systems improve recycling efficiency, while data-driven routing minimizes the fuel consumption of collection vehicles. Despite these technological advancements, the documents identify significant hurdles, including high equipment costs, a lack of standardized datasets, and a need for greater public awareness. The collective research emphasizes transitioning from traditional linear disposal methods to a circular economy that prioritizes resource recovery. Furthermore, case studies from various countries illustrate how digital platforms and robotics can optimize urban sanitation while reducing environmental pollutants. Ultimately, the literature suggests that achieving long-term sustainability requires a blend of innovative technology, supportive government policy, and active citizen engagement.

The IoT Infrastructure:

Smart Garbage Bins (SGBs) with ultrasonic sensors, load cells, and wireless communication (LoRaWAN, NB-IoT).

Real-time monitoring of fill levels, gas emissions, and bin status.

- Sensing Capabilities: These bins are equipped with ultrasonic sensors to measure fill levels and load cells or weight sensors to measure the exact mass of food waste. Additional sensors, such as gas detectors, identify hazardous substances like methane or ammonia to prevent environmental risks.
- Communication Networks: SGBs exchange information using wireless mesh networks (WMN), allowing for high reliability and service continuity even across wide service domains. Data is transmitted via CDMA or GPRS modules to centralized servers for analysis.
- Energy Efficiency: To ensure mobility and low maintenance, these bins are often battery-powered and utilize energy-efficient sleep modes, only "waking up" during user authentication or data request cycles from a router.

AI and Predictive Analytics:

AI and Predictive Analytics is a powerhouse combination that's transforming decision-making across every industry.

AI enhances predictive analytics by:

- Handling Unstructured Data: AI can process text (emails, social media), images (X-rays, product photos), and audio to find predictive signals.
- Automating Feature Engineering: AI can automatically discover the most relevant data points (features) that influence outcomes, rather than relying solely on human experts.
- Continuous Learning: ML models can continuously improve their predictions as new data flows in.

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- Greater Accuracy & Scale: Deep learning models can find complex, non-linear patterns in massive datasets that traditional statistics miss.
- ANN and Random Forest models for waste forecasting
- Dynamic route optimization reducing fuel use
- Robotic sorting systems

4. Robust Policy Framework:

A comprehensive framework requires multiple, reinforcing elements:

A. Regulatory & Legislative Instruments

- Extended Producer Responsibility (EPR): A cornerstone policy. Makes producers financially and/or physically responsible for the end-of-life management of their products (e.g., packaging, electronics, batteries).
- Landfill Bans & Restrictions: Prohibits specific waste types (e.g., organic waste, recyclables) from being landfilled, forcing diversion to higher levels of the hierarchy.
- Product Standards: Mandates durability, repairability (e.g., EU's "Right to Repair"), and recyclability. Bans hazardous materials.
- Mandatory Separate Collection: Laws requiring municipalities or businesses to separately collect key streams like paper, plastic, glass, metals, and organics.
- Permitting & Licensing: Strict environmental permits for waste treatment facilities (landfills, incinerators, recycling plants) to control pollution.

B. Economic & Market-Based Instruments

- Pay-As-You-Throw (PAYT): Households pay for waste collection based on the amount of non-recyclable waste they generate, creating a direct financial incentive to recycle.
- Landfill & Incineration Taxes: Increasing the cost of disposal makes recycling and prevention more economically attractive.
- Deposit-Return Schemes (DRS): Consumers pay a small deposit on beverage containers, refunded upon return. Drastically increases collection rates for high-quality recycling.
- Green Public Procurement (GPP): Governments use their purchasing power to buy recycled-content products, creating a stable market for secondary materials.
- Subsidies & Grants: Support for recycling infrastructure, innovation in waste-to-resource technologies, and circular economy startups.

C. Levels of Policy Action

- International: Basel Convention (controls transboundary movement of hazardous waste), UN Sustainable Development Goals (SDG 12: Responsible Consumption and Production), OECD recommendations.
- Supranational (e.g., European Union): Sets binding directives and targets for member states (e.g., Circular Economy Package, Single-Use Plastics Directive).

- National/Federal: Enacts core laws, sets national targets, and implements schemes like EPR.
- State/Regional: Often responsible for permitting facilities and regional planning.
- Municipal/Local: Directly responsible for household waste collection, operating/local licensing of treatment facilities, and local enforcement (e.g., bin inspections).

D. Major Global Models & Trends

- The European Model: Highly regulated, target-driven, and based on the "polluter pays" principle. Heavily relies on EPR and high landfill taxes. The EU is a global leader in circular economy policy.
- The Japanese Model: Focus on meticulous source separation by citizens (often into 10+ categories), enforced by local communities. Strong emphasis on waste-to-energy (incineration) due to limited land, paired with the "3Rs" (Reduce, Reuse, Recycle) national framework.
- Emerging Economy Challenges & Innovations: Often face issues with informal waste sectors. Effective policies focus on integrating and formalizing waste pickers, building basic collection infrastructure, and leapfrogging to circular solutions (e.g., India's focus on plastic waste EPR and Rwanda's strict ban on non-biodegradable plastic bags).

5. Analysis of waste management:

Waste management system has various criteria on which the success of the system depends, following is the critical analysis of the various criteria and the major leader of waste management.

Criteria	South Korea	European Union	United States	Japan
IoT Adoption	High (nationwide SGBs, RFID, real-time networks)	Moderate (pilots in smart cities)	Low to moderate (private-sector led)	High (focused on Tokyo, Osaka)
AI Integration	Advanced (predictive analytics, robotic sorting)	Growing (AI in sorting, limited in collection)	Emerging (corporate R&D)	Advanced (robotics, vision systems)
Policy Framework	Advanced (predictive analytics, robotic sorting)	Strong (EU Green Deal, circular economy directives)	Fragmented (state-level regulations)	Strong (national waste laws, recycling targets)

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Public Engagement	High (PAYT, incentives, strict enforcement)	Moderate (awareness campaigns, variable compliance)	Low to moderate (voluntary programs)	High (cultural emphasis on cleanliness)
Recycling Rate (Food Waste)	95%	50–70% (varies by country)	30–40%	80–85%
Emission Reduction	29–30% (from optimized routing)	15–25%	10–20%	20–25%
Cost Efficiency	High after initial investment	Moderate	Low to moderate	High
Key Technologies	SGBs, RFID, AI routing, robotic sorters	Smart bins, blockchain traceability	Automated trucks, MRF AI	Pneumatic waste pipes, robotic sorting

5. Critical Challenges & Barriers

Technical & Infrastructure

1. Interoperability: Proprietary systems creating data silos
2. Connectivity: Remote/rural areas lacking network coverage
3. Power Supply: Battery life limitations for IoT devices
4. Data Quality: Sensor accuracy and calibration issues

Economic & Operational

1. High Initial Value: Smart bins cost 3-5x traditional bins
2. Return on Investment Uncertainty: Many municipalities lack lifecycle cost analysis
3. Skills Gap: Shortage of AI/data science talent in public sector
4. Maintenance Complexity: Specialized technicians required

Regulatory & Social

1. Data Privacy: Concerns about tracking individual waste patterns
2. Resistance to Change: Union concerns in traditional waste sectors
3. Policy Lag: Regulations not keeping pace with technology
4. Digital Divide: Exclusion of low-income/elderly populations

1. Discussion

The success of IoT and AI with the digitation of the system is depend on Policy and Governance, Technology Deployment and Participation of Stakeholder. The technological development and its integration in the waste management have been the real issue in the developing countries, where as developed countries are now heading towards the complete digitisation of the waste management system.

South Korea's success is attributable to:

1. Holistic system design linking IoT, AI, and policy.
2. Strong legislative backing with circular economy targets.

3. Public compliance mechanisms (RFID, adaptive pricing, fines).
4. Continuous innovation (e.g., Ecube Labs, digital twins).
5. Limitations includehigh upfront costs and data standardization challenges. The comparative analysis suggests that nations with centralized waste policies and public-private partnerships achieve better outcomes.

7. Conclusion and Recommendations

IoT- and AI-driven waste management system offers a replicable model for sustainable urban waste management. Technology alone isn't sufficient. The most successful implementations (Singapore, Barcelona, Seoul) combine IoT/AI with strong policy frameworks, stakeholder engagement, and business model innovation. The future lies not in "smart waste management" but in "intelligent resource management systems" where waste is eliminated through predictive design and circular flows.

Key recommendations for other nations include:

- Develop national circular economy laws with clear Key Performance Indicators.
- Invest in IoT infrastructure and interoperable data platforms.
- Implement incentive-based PAYT systems to drive public participation.
- Foster innovationthrough public-private R&D partnerships.

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