

POLICYBRIEF

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Accelerating the Transition to a Circular Economy through Data-Driven Waste Management

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Highlights

1. Data-driven waste management can accelerate the transition to a circular economy
2. Emerging technologies for collecting and using data in waste management are promising
3. Data-driven insights can improve operational efficiency, transparency, recovery performance and evidence-based policies in waste management
4. However, to scale data-driven waste management beyond demonstrator projects, several barriers need to be overcome

Introduction

Rapid population growth, accelerated urban expansion, and ongoing economic development have substantially increased both the quantity and complexity of waste, intensifying associated environmental and governance challenges. Global projections indicate that annual waste generation across municipal, industrial, construction, and hazardous sectors may surpass 3.4 billion tons by 2050, up from approximately 2 billion tons in 2020. Suboptimal waste handling continues to intensify greenhouse gas emissions, contaminate ecosystems and lead to the loss of valuable secondary materials. Reducing waste, along with recovery, reuse and recycling waste, is therefore an urgent global priority.

As countries confront near-saturated landfill capacity and resource scarcity, circular economy approaches that sustain materials in productive cycles through reuse, remanufacturing, and high-quality recycling are gaining prominence. Beyond reducing environmental impacts, the circular economy positions waste as a potential economic asset and a catalyst for industrial innovation. Data-driven insights that inform planning and operation of waste management and material flows can accelerate the transition to a circular economy.

Emerging digital technologies are reshaping material recovery, reuse and recycling by improving operational efficiency





Mixed plastic packaging waste (Photo source: K-eco)

and effectiveness, while at the same time constantly providing data to guide waste management. Smart meters, transportation-tracking, Internet of Things (IoT) sensors, digital municipal ledgers, automated sorting and even citizen-contributed data are leading to a more detailed picture of how waste is produced and handled across a city. Machine-learning models are now fairly commonly used for predicting short-term variations or seasonal patterns in municipal waste quantities. Composition-based forecasting is used by researchers to inform planning treatment capacity and recycling markets. Data-driven tools are used to estimate landfill expansion and remaining operational life, traditionally done through tedious manual surveys. Digitalisation advances in e.g., decision-support systems, help address complexities in planning and policy evaluation.

Data-Driven Opportunities at Different Stages of Waste Management	
Generation	Avoid waste by designing products informed by data about waste
Monitoring	Monitor and track hazardous waste to prevent mismanagement and protect the environment
Collection and Transport	Improve efficiencies and save costs by optimising routes based on location-based data, wastebin monitoring (IoT) and predictive analytics
Sorting and Recovery	Increase recycling rates with automated identification, classification and sorting of waste (machine learning, neural networks)
Disposal	Improve efficiencies by routing to landfills, finding suitable locations for landfills
Policies	Analyse, review and adjust policy documents with text mining and natural language processing (LLM)

Effective waste reduction and resource recovery require reliable waste data, standardised reporting systems, and enabling legal and institutional frameworks. Together, they make transparent, efficient and effective evidence-based waste management possible, as the example from South Korea shows.

**Example from South Korea:
Integrating Legal Frameworks with Digital Waste Tracking**

South Korea is a practical example of how legal and institutional frameworks can support data-driven waste management. The country has developed the nationwide ALLBARO system under the Waste Management Act to digitally track industrial waste movements. The system provides an electronic manifest that enables end-to-end tracking of industrial waste from generation to final treatment. It improves transparency, prevents illegal disposal, supports compliance monitoring, and provides reliable data for evidence-based policymaking.

Despite rapid advances and growing interest in data-driven waste management, several challenges to scaling up these emerging technologies remain.

Technical and Infrastructure Barriers

Most waste systems operate with legacy infrastructure that was not designed for sensors, robotics or advanced analytics. Retrofitting AI-enabled sorting and monitoring often requires significant capital expenditure, changes to plant layout, and extensive software integration work, due to compatibility problems with existing conveyors, optical sorters, weighing systems and enterprise software.

Data Availability, Quality and Fragmentation

Effective data-driven waste management depends on consistent, multi-dimensional datasets spanning climate, technology, demographics, regulation and socio-economics. In practice, many records are still collected manually, with limited standardisation, which leads to missing values, inconsistent categorisation and poor temporal resolution. Particularly in developing contexts, there is still a basic struggle with data scarcity and lack of synchronised databases.

Proprietary data are another barrier: substantial fractions of data about waste collection and waste treatment are held by private operators and not released for research or model training.

Transparency and Bias

Many of the most powerful AI tools, such as deep neural networks, ensemble models and complex optimisation routines, are “black boxes” from the perspective of waste managers as end users. Their internal logic is rarely transparent, which makes it difficult for practitioners to understand and justify certain recommended site selections, tariffs or service levels. This opacity slows adoption, particularly where decisions carry potential public health or environmental risks.

Privacy, Security and Regulatory Constraints

Data-driven waste management relies on highly granular information: household-level waste statistics, location-based collection routes, and, increasingly, behavioral data linked to pay-as-you-throw schemes or smart-bin usage. These data streams raise familiar concerns about ownership, consent and the potential misuse of personally identifiable information. Additionally, the integration of IoT devices increases vulnerability to cybersecurity breaches, with implications for both data integrity and operational continuity.

A Resource Nexus Perspective

The Resource Nexus recognises the interdependencies among environmental resources such as water, energy, material, land, climate and waste. Data-driven waste management allows identifying and quantifying synergies and tradeoffs between environmental resources, e.g.,

- optimising synergies between climate (greenhouse gas emissions), land (landfills) and materials (recycling); and
- balancing trade-offs between waste-to-energy conversion and waste reuse or recovery as a secondary material in a circular economy.

Data-driven waste management therefore contributes not only to recycling but also to broader resource efficiency, climate mitigation, and environmental sustainability.



Privacy-enhancing techniques, anonymisation, encryption, strict access control, and evolving regulatory frameworks help mitigate some of these risks. However, compliance with data-protection rules adds complexity and cost, especially for smaller municipalities.

Social and Ethical Implications of Automation

Robotics and AI-enabled automation can dramatically increase waste throughput and reduce manual exposure to hazardous materials. At the same time, this raises flags about job displacement, changing skill requirements and the distribution of risks and benefits across communities. Environmental justice debates raise concerns about such novel technologies: waste facilities and technologies are often located in already disadvantaged neighborhoods, and algorithmic choices may, unintentionally, reinforce these patterns.

Institutional Capacity and Awareness

Many stakeholders in the waste sector do not yet see data as a core strategic asset in the same way that, for instance, organizations in the pharmaceutical or finance sectors do. Awareness of benefits remains limited, and capacity to commission, interpret and maintain such systems is uneven.

Conclusion

Data-driven waste management offers a pivotal opportunity to shift waste management from end-of-pipe disposal towards predictive and adaptive governance of circular resource flows.

Future-ready data-driven waste management must be digital, decarbonised and embedded in circular economy strategies.

Realising and leveraging this opportunity requires coordinated technological, institutional and socio-economic change. Challenges for wider adoption and scaling of impressive technical demonstrations in waste management need to be addressed before data-driven waste management can deliver on its environmental and circular economy promise.

Waste management practices vary across the globe. Countries with strong legal frameworks and enforcement coupled with well-developed digital platforms tend to have higher recycling rates and more effectively implement circular economies, helping them to achieve carbon neutrality goals.

However, the transition to data-driven waste management is unlikely to occur uniformly across countries. Particularly in developing countries, digital transformation should be implemented progressively according to national capacities, beginning with reliable data collection and standardised reporting systems before introducing advanced AI applications.

Action Points

1. Strengthen legal and institutional frameworks for standardised waste data governance and interoperability
2. Invest in digital infrastructure, organisational capacity, and workforce skills to enable data-driven waste management
3. Promote transparent and explainable AI to improve trust, accountability and wider adoption
4. Balance innovation with privacy protection, cybersecurity, and ethical safeguards
5. Support the transition to a circular economy through progressive implementation of data-driven waste management tailored to national capacities

Reference

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