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REVIEW ARTICLE

Artificial Intelligence and the Internet of Things for Sustainable Waste Management

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ABSTRACT

Urbanisation and rising consumption increase the demands placed on waste services in the Middle East and North Africa (MENA). This study examines how artificial intelligence (AI) and the Internet of Things (IoT) can support waste collection and material recovery within a circular economy. It uses a qualitative narrative review of selected academic and institutional sources, with regional examples and comparative evidence from outside MENA. The analysis distinguishes sensor-based monitoring, route optimisation and image classification from wider claims about environmental performance. Published studies report potential operational gains, but their results depend on the system, setting and evaluation method. In particular, the TUHR system for Makkah is a proposed and developed system with limited testing under actual operating conditions, rather than evidence of citywide deployment. The review also considers the energy and material requirements of digital equipment, privacy and the role of workers. AI and IoT can support more responsive waste services, but their net contribution to sustainability requires local evaluation, reliable data and accountable governance.

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1. Introduction

Urbanisation and changing consumption patterns increase the volume and complexity of waste that municipalities must manage. Waste services need to protect public health while supporting waste prevention and material recovery. Kaza et al. (2018) describe the global scale of this challenge and the differences between waste systems across countries.

The World Bank (2026) estimates that MENA generates about 155 million tonnes of municipal solid waste annually, with volume projected to reach 294 million tonnes by 2050 without further action. It reports less than 10% recycling, substantial mismanagement and annual environmental damage of about USD 7.2 billion. These figures concern municipal solid waste and should be distinguished from national accounts covering waste from all economic activities.

The central question is: How can AI and IoT support waste-management services relevant to the circular economy in MENA, and what conditions limit their environmental and social benefits?

Three analytical propositions guide the review:

P1: IoT monitoring can reduce gaps in information about waste volumes and collection needs when actors share accurate, timely data.

P2: Combining sensor data with prediction and optimisation can improve collection and sorting, with benefits that depend on local operating conditions.

P3: The environmental and social value of digital waste systems depends on governance that addresses equip-

ment, energy, data and worker impacts.

The review pursues the following objectives:

To examine how AI and IoT can support information sharing and coordination across waste collection and recovery activities.

To assess reported operational gains while distinguishing proposals, simulations and field evaluations, and separating regional evidence from examples outside MENA.

To consider technical constraints, material and energy requirements, and questions of privacy and inclusion when proposing governance priorities.

The discussion links these objectives to the circular economy, responsible digital practice and the twin transition, understood here as the coordination of digital development with environmental goals.

2. Review approach and conceptual framework

This study uses a qualitative narrative review of selected research papers, institutional reports and documented regional initiatives. The sources span 2016-2026. The synthesis compares the functions, reported outcomes and limitations of digital waste systems; it does not pool effect sizes or present an exhaustive systematic review. Regional statistics provide context, while the technical examples illustrate different levels of evidence. The three propositions organise the discussion and are not statistically tested hypotheses.

2.1. *From the linear economy to circular resource use*

The circular economy seeks to retain the value of products and materials through prevention, reuse, repair and recycling. Ghisellini et al. (2016) review its principles and implementation across different scales. Digital tools may assist coordination, but circular practices also require appropriate product design, collection arrangements and markets for recovered materials.

Özsoy (2023) reviews potential AI applications in resource management and circular business models. Prediction and classification may support decisions about maintenance, recovery and material flows. These are possible applications rather than proof that AI adoption automatically produces circular outcomes.

2.2. *Responsible digital practice and organisational accountability*

Corporate social responsibility provides a framework for considering stakeholder interests alongside organisational performance. Grünfelder and Delalieux (2023) discuss responsible practices, including the digital context. For waste operators, this perspective includes the effects of sensors, software and automation on workers, service users and the environment.

Traceable records can support sustainability reporting, but their value depends on data quality and clear responsibility for collection and verification. Cigref (2026) discusses these governance issues in its report on digital departments and sustainability reporting. Digital records alone do not establish regulatory compliance or the accuracy of an environmental claim.

2.3. *The twin transition*

The twin transition concerns the relationship between digital development and environmental objectives. The OECD (2024) identifies opportunities for digital technologies to support environmental performance while recognising their own environmental footprint.

For waste management, the relevant question is whether operational gains outweigh the impacts of equipment manufacture, communications, computation and disposal. A useful assessment therefore considers the whole service and its life cycle rather than treating digitalisation as an environmental benefit in itself.

Table 1 maps selected circular-economy objectives to possible digital functions. It presents conceptual links rather than measured effects or guaranteed performance thresholds.

Table 1 Circular economy objectives and possible digital functions

Circular economy objective	Digital function	Potential contribution
Product and service design	Digital twins and simulation	Compare options for resource use before implementation
Longer equipment life	Condition monitoring and predictive maintenance	Identify maintenance needs and avoid preventable replacement
Collection planning	Fill-level sensors and route optimisation	Reduce unnecessary visits where local evaluation supports a change
Material sorting	Computer vision and validated sensing	Assist identification and separation; output quality requires measurement
Material-flow traceability	Shared digital records, including blockchain where appropriate	Improve records for verification; accuracy depends on physical checks and data quality

Source: Author synthesis based on Ghisellini et al. (2016), Özsoy (2023) and Kannan et al. (2024). The contributions are potential benefits that require evaluation in the intended setting.

3. Technological architecture of smart waste management

3.1. *Sensing and connectivity*

IoT devices can provide operators with observations about bins and collection vehicles. Systems described in the literature combine sensors, communication links and a platform for storing or displaying data (Abdullah et al., 2022; Al Qurashi et al., 2026). Their practical value depends on calibration, maintenance and reliable communication.

Ultrasonic sensors estimate fill level from the distance between the sensor and the waste surface. Irregular contents can affect the reading, so a volume estimate should not be treated as a direct measurement of waste mass.

Cameras and other sensors may support material identification or contamination checks. Performance depends on the materials, lighting and sensing method, and the classification requires validation against labelled observations.

Location devices can support the tracking of vehicles and bins. Operators can combine these observations with collection records when planning routes.

Communication options include low-power wide-area networks and cellular connections. Addas et al. (2024) describe a LoRaWAN and cellular architecture. Network choice should reflect coverage, battery requirements and cost. Billing by weight or volume would also require suitable measurement and service rules; a digital bin identifier alone does not make charging more equitable.

3.2. *Analysis and optimisation*

Sensor data can support two related tasks: planning collection and identifying materials. Prediction estimates future conditions, while route optimisation selects collection plans subject to constraints such as vehicle capacity and service priorities. These functions need not all use the same form of AI.

Algorithms can use current fill levels and collection histories to prioritise bins and calculate routes. Kannan et al. (2024) review Industry 4.0 applications across waste-management activities and propose a framework connecting technologies, processes and circular strategies.

Computer vision can assist image-based classification for sorting. A high image-classification score, however, is distinct from the purity or recovery rate of a physical output stream. Evaluation should examine the actual materials, contamination and sorting equipment rather than transfer a model score to an entire facility (Kannan et al., 2024).

3.3. *Digital twins and traceability*

Digital twins can represent parts of a waste system for scenario analysis, such as changes in collection frequency or facility use. Their usefulness depends on whether the underlying model and data represent operating conditions. A simulation cannot establish the outcome of an investment before that outcome is observed.

Digital records, including blockchain-based systems, may help actors share a history of material movements. Their integrity still depends on accurate entries and verification of physical flows. A ledger cannot by itself guarantee the origin of materials, prevent false reporting or prove that recycling has occurred (Kannan et al., 2024).

4. Regional examples and waste-sector context

4.1. *Saudi Arabia and the Makkah examples*

Saudi Arabia's General Authority for Statistics (GASTAT, 2025) reports 135.1 million tonnes of recorded waste in 2024, covering economic activities and households. This total is broader than municipal waste. Separately, the national waste-management plan includes a target to divert 90% of waste from landfill by 2040 (Saudi Press Agency, 2025). Diversion is a wider objective than material recycling, and the target describes a policy ambition.

Table 2 Selected categories in Saudi recorded waste accounts for 2024

Classification	Selected category	Quantity (million tonnes)	Share of recorded total (%)
Economic activity / households	Agriculture, forestry and fishing	46.9	34.7
Economic activity / households	Construction	32.2	23.8
Economic activity / households	Households	20.5	15.2
Economic activity / households	Manufacturing	18.3	13.5
Waste type	Organic waste	61.7	45.7
Waste type	Plastic waste	7.8*	5.8

*Source: GASTAT (2025), Waste Statistics in Saudi Arabia 2024. Shares use the recorded total of 135.1 million tonnes; values are rounded. The selected categories are not exhaustive. Classification by economic activity and classification by waste type describe the same overall total from different perspectives and must not be added together. *The plastic-waste quantity is calculated from 135.1 million tonnes multiplied by the reported 5.8% share and rounded to one decimal place.*

Al Qurashi et al. (2026) present TUHR, a smart waste-management system designed for Makkah. It combines sensor observations with a cloud platform and interfaces for collection staff and administrators. The authors describe difficulties obtaining real-world data and identify testing in actual operating conditions as further work. TUHR therefore illustrates system development and feasibility rather than a demonstrated citywide operational effect.

Abdullah et al. (2022) evaluate collection scenarios through C++ and MATLAB simulation with randomly assigned bin conditions. Their abstract reports a 46% reduction in locations and bins requiring visits under the simulated conditions. The paper also describes a separate infrastructure approach in Makkah: pneumatic transport through a 30 km underground network with capacity to move 600 tonnes per day. This background example illustrates transport capacity, while the simulation examines collection decisions. Table 2 presents the national statistical context.

4.2. *Other regional examples*

In Abu Dhabi, TWMA (2025) reports the start of operations at its Habshan drill-cuttings treatment facility. The operator describes a design capacity of up to 300 tonnes per day and real-time tracking and analytics through its Xlink platform. This is an industrial-waste example. Design capacity is not the same as measured daily throughput, and the operator announcement does not establish a separate causal effect of AI.

Qatar News Agency (2023) describes government initiatives for sorting at source and the recovery of waste through recycling, energy production and composting. These pathways have different outputs and environmental implications. Their treatment together in policy statements should not be interpreted as a material-recycling rate or as evidence that AI caused the reported progress.

5. Economic and environmental implications

5.1. *Reported operational gains and their interpretation*

Addas et al. (2024) report a pilot involving 10 locations in Lahore, Pakistan. Their published results include a 32% reduction in route distance, 29% lower fuel consumption and 18% lower vehicle-maintenance costs relative to conventional practices. The study combines sensor monitoring with route simulation. These source-reported results provide comparative evidence from outside MENA, with transferability requiring evaluation in the intended setting. Separately, the World Bank (2026) estimates that a 1% reduction in MENA waste generation could save up to USD 150 million annually. This regional scenario concerns waste prevention rather than the effect of a particular digital system.

Material recovery may create revenue when operators can supply suitable materials to buyers. The size of the market provides context rather than a return-on-investment estimate for a particular technology. Grand View Research (2025) estimates the Middle East waste-management market at USD 58.06 billion in 2024 and forecasts USD 104.05 billion by 2033. This is a commercial forecast for the market defined in that report, not an observed outcome or evidence that AI alone drives growth.

5.2. *Work and inclusion*

The World Bank (2026) reports around 400,000 formal workers in the regional solid-waste sector and at least as many informal workers. Digital systems may change the skills and tasks required, including equipment maintenance and data management. The review does not estimate net job creation or displacement.

Planning should consider how informal waste workers can participate in collection and recovery arrangements. Training, access to information and consultation can support this process, but digital registration alone does not secure income or remove exclusion. The effects on different worker groups require local evidence.

5.3. *Environmental performance*

Fewer vehicle kilometres may reduce fuel use, while improved sorting may support material recovery. Net environmental performance also depends on treatment choices, equipment and electricity use. The different measures should be assessed separately; a reduction in fuel consumption does not by itself establish the same percentage reduction in the life-cycle footprint of the waste service (OECD, 2024).

6. Environmental and ethical constraints

6.1. *Materials and equipment*

Digital waste systems require physical devices, communications equipment and computing infrastructure. Izoard (2024) examines the material demands of technologies associated with the transition and the impacts of mineral extraction. Assessing a digital waste service therefore requires attention to the equipment supply chain as well as operations.

Equipment life, repairability and end-of-life management affect the material demands of a system. Reuse and recycling of devices may reduce some impacts, but they do not create a fully closed material loop. Operators should consider whether a proposed function justifies additional hardware.

6.2. *Energy use and the footprint of computation*

The energy requirements of computing vary with the model, workload and infrastructure. The Shift Project (2025) examines AI, data and computing infrastructure in relation to decarbonisation. For a waste-management service, evaluation should identify the workload attributable to the application and the infrastructure supporting it.

Possible design choices include simpler models, reduced data transfers and processing near the sensor. These choices require evaluation: moving computation to the edge does not automatically reduce the total environ-

mental footprint. Comparisons should include the relevant equipment, communication and processing requirements.

6.3. *Privacy and algorithmic accountability*

Cameras, location records and identifiable service data can affect privacy. Operators should define the purpose of collection, limit access and retention, and apply the requirements of the relevant jurisdiction.

Route-planning systems can also reproduce inequalities if their objectives or input data favour some districts. Evaluation should check service coverage and waiting times across neighbourhoods. Human oversight and a way to challenge errors are relevant safeguards when algorithmic recommendations affect public services.

7. Governance and public policy

7.1. *Coordination across stakeholders*

Implementing digital waste services requires agreement on service goals, responsibilities and the handling of data. The following roles provide a basis for coordination:

Public authorities can define service obligations, reporting requirements and procurement conditions, with attention to the capabilities of local operators.

Private providers can supply equipment, software and operational services. Contracts should make maintenance, interoperability and performance responsibilities clear.

Universities and research organisations can assist with skills development and independent evaluation, including life-cycle assessment.

Workers, service users and community organisations can help identify access problems, practical constraints and priorities for service improvement.

7.2. *Digital records and regulatory capacity*

Digital tracking can improve the availability of records for inspections and service planning. Authorities still need procedures for checking data, investigating discrepancies and acting on findings. An electronic record should support oversight rather than substitute for verification of physical waste movements.

Regional cooperation can assist the exchange of experience and the development of compatible data definitions. Any cross-border waste arrangements also require attention to the applicable national and international requirements. The review does not propose a single regulatory model for all MENA countries.

8. Discussion

8.1. *Interpretation of the evidence*

The reviewed sources show several ways to connect waste observations with operational decisions. They cover different activities and levels of development, so their findings should not be combined into a single estimate of AI and IoT performance across MENA.

The distinction between system design and measured outcomes is central. A prototype can demonstrate communication between components; a simulation can examine a routing rule under stated assumptions. Evidence of service performance requires observations under actual operating conditions.

For collection, the Lahore pilot provides a reported operational example, while the Makkah simulation examines a proposed collection strategy (Addas et al., 2024; Abdullah et al., 2022). Their percentages refer to different outcomes and settings. A reduction in stops, a shorter route and lower fuel use are related possibilities, but they are not interchangeable measures and cannot be multiplied or pooled without a common design.

For recovery, image classification is one part of the sorting process. Feedstock quality, physical separation and markets for recovered materials also matter. The review provides no common basis for claiming a universal classification accuracy or recycled-material purity.

The regional examples underline the need to distinguish treatment capacity from demonstrated improvements in collection and recovery. Operational trials in high-density settings would strengthen the evidence on scalability and service performance.

8.2. *Implications for the analytical propositions*

The sources provide grounds for considering the three propositions, with different strengths of evidence for each. The review does not conduct a statistical or experimental test.

The following interpretations follow from the synthesis:

P1 identifies a plausible information mechanism: sensors can make collection needs more visible. Reliability and data sharing remain conditions for that mechanism to work. The simulation reported by Abdullah et al. (2022) illustrates this approach under assigned bin conditions; field observations would help assess its practical effect.

P2 concerns potential operational improvements. Source-reported gains in a particular setting support further evaluation, but they do not establish a common regional effect or prove the independent contribution of AI within a combined system.

P3 directs attention to governance and the digital system's own impacts. The energy, equipment and stakeholder issues discussed here justify including these dimensions in evaluation, without treating the proposition as empirically validated.

The practical implication is to assess whether a digital system improves the intended waste service at an acceptable environmental and social cost. The appropriate balance may differ between municipalities and waste streams.

9. Limitations and directions for research

9.1. *Limitations*

This narrative review brings together selected sources and examples. It does not provide an exhaustive search protocol, a formal risk-of-bias assessment or a pooled effect estimate. Selection and publication bias may therefore affect the evidence presented.

The regional examples concern particular national or urban settings, while the Lahore study provides comparative evidence outside MENA. These examples cannot represent the conditions of every municipality, especially rural or lower-resource services.

The quantitative claims are secondary, source-reported results. The underlying methods differ, including simulation, pilot monitoring and operator reporting. The review does not independently reproduce those studies, and their figures cannot establish an average regional benefit. National all-waste accounts, regional municipal-waste estimates and commercial market forecasts also have different scopes.

The study does not calculate a complete life-cycle assessment of sensors, communications and computing. It therefore cannot quantify the net environmental benefit of a particular deployment. Long-term evidence on equipment failure, service coverage and worker outcomes is also needed.

9.2. *Policy implications*

The review links information gaps in waste services with circular-economy aims and responsible digital practice. Its contribution is a conceptual synthesis and an account of the limits of the available examples rather than a newly validated performance model.

The following priorities follow from that analysis:

Interoperability and maintenance: Specify data formats, interfaces and maintenance responsibilities before procurement. Select communication technologies according to local coverage and service needs rather than assuming that one protocol fits all settings.

Environmental procurement: Consider equipment life, repairability, electricity demand and end-of-life treatment when comparing bids. Require suppliers to document the assumptions behind environmental claims.

Worker and community participation: Combine technical trials with consultation and support for source separation. Evaluate participation and access without assuming that awareness campaigns will produce a particular sorting-accuracy percentage.

Performance monitoring: Compare the system with a documented baseline and report route distance, fuel, recovery and service coverage as separate measures. Include the relevant digital infrastructure when evaluating net environmental effects.

9.3. *Future research*

Further work should address the following areas:

Long-term field evaluation: Compare service performance before and after deployment, or use suitable comparison areas. Record waste volumes, route conditions, equipment downtime and costs to support an assessment of operational resilience and return on investment.

Life-cycle assessment: Compare operational savings with equipment manufacture, energy use, communications and end-of-life treatment. Use local data rather than importing a percentage from an unrelated pilot.

Governance and distribution: Examine data ownership, privacy, service coverage and effects on formal and informal workers. Test how consultation and contract arrangements influence outcomes.

10. Conclusion

AI and IoT can support the monitoring, planning and analysis of waste services, but sustainability depends on how they are used. This review distinguishes source-reported pilot results, simulations and proposed systems from regional waste statistics and policy ambitions. The evidence supports targeted evaluation of collection and recovery functions; it does not establish a universal percentage benefit or confirm the three analytical propositions. For MENA, deployment decisions should consider local service needs, reliable data, equipment and energy demands, and the people who operate and use the system.

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