Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/GC03.20260106
Published: February 2, 2026

Benchmarking Smart Waste Systems: A Strategic Pathway for Egypt's Circular Economy Transition

Ghada M. A. Younes, Reem Al-Kadeem, Nermine Harraz and Ahmad E. Elhabashy
Production Engineering Department
Faculty of Engineering, Alexandria University, Egypt
ghada.younes17@alexu.edu.eg

Ghada M. A. Younes
Arab Academy for Science
Technology & Maritime Transport, Alexandria, Egypt
ghada.younes@aast.edu

Abstract

Egypt's Municipal Solid Waste (MSW) system faces critical challenges, including rising volumes, fragmented governance, and low recovery rates. To generate insights for reform, this study benchmarks four international city models using a *five-lens framework* covering policy, service design, infrastructure, data, and social systems. Each case demonstrates how smart technologies and governance models drive recovery. Findings are projected to Egypt, with a focus on Alexandria, a coastal city that faces both seasonal surges and structural inefficiencies. A phased *traffic-light strategy* is proposed sequencing; near-term measures (segregation pilots, GIS-based routing, and awareness campaigns), medium-term reforms (IoT monitoring, extended producer responsibility, and recovery capacity), and long-term investments (fleet electrification and pneumatic conveyance). Beside benchmarking, the paper introduces the *Circular Economy–Embedded Garbage Truck Vehicle Routing (CE-GTVR)* framework as a conceptual step toward *Circular Economy 2.0.* CE-GTVR integrates segregation quality, recovery potential, and emissions per ton into routing logic, aligned with Egypt's Law 202/2020 and Vision 2030. While only conceptually validated, the framework outlines future pathways for empirical testing. By situating Egypt's transition within global and regional discourse, this study contributes a roadmap that is actionable, phased, and transferable to Gulf Cooperation Council (GCC) and Middle East and North Africa (MENA) contexts.

Keywords
Benchmarking, Circular Economy, Reform Policies, Smart Waste Management, Vehicle Routing

1. Introduction
Municipal Solid Waste (MSW) management is a defining sustainability challenge for urbanizing economies. Global waste is projected to increase from 2.01 billion tons in 2016 to 3.4 billion tons by 2050 (World Bank 2018), as shown in Figure 1.

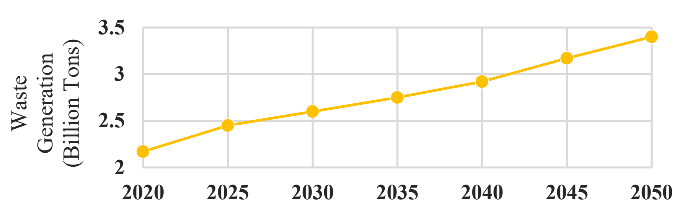

Figure 1. Global MSW generation projections, 2020–2050 (Adapted from World Bank 2018)

In Egypt, more than 95 million tons of waste are generated annually, yet only 60–65% is formally collected and less than 20% is recovered; over 70% ends up in landfills or is openly dumped (WMRA 2021; CAPMAS 2022). Recovery remains below 20%, and the system is concentrated at the lowest tiers of the waste hierarchy, relying on disposal rather than prevention, reuse, or recycling. The hierarchy itself prioritizes recovery and circularity over landfilling (Figure 2). Ongoing reforms, particularly Egypt's Vision 2030[1] and Law 202/2020, aim to shift this path (GIZ, 2022; OECD, 2024; Khafagy et al., 2024).

Figure 2. Waste hierarchy in circular economy-aligned MSW systems

Structural challenges include fragmented mandates, weak enforcement, and chronic underfunding. Waste Management Regulatory Authority (WMRA) contracts have introduced infrastructure upgrades; however, local capacities remain overstretched and private-sector involvement is limited. The waste profile indicates potential for composting, Anaerobic Digestion (AD), and recycling, provided that segregation and infrastructure are supported (WMRA, 2021; CAPMAS, 2022; GIZ, 2022). Alexandria's seasonal peaks exceed 5,000 tons/day (Elgazzar et al. 2017; Khafagy et al. 2024). National legislation—particularly Law 202/2020—positions Circular Economy (CE) as a strategic pillar of Egypt's Vision 2030. However, while different international cities have embedded CE principles through digital monitoring, policy innovation, and infrastructure investment, Egypt still faces weak municipal regulations, limited digital capacity, and financial constraints. This gap leaves CE goals misaligned with the daily logistics of collection, segregation, and recovery.

1.1 Objectives

This study aims to address the gap of Egypt's MSW system within global CE discourse and smart waste models. The study focuses on the following four core objectives, addressed through four different frameworks.

1. **Diagnose Egypt's gaps:** Identify structural and operational deficits in Egypt's MSW system.
2. **Benchmark global cities:** Benchmark international smart waste models through a five-lens framework.
3. **Develop a phased roadmap:** Propose a phased traffic-light strategy for pilots, reforms, and long-term alignment with Vision 2030 and the SDGs.
4. **Outlining a future research pathway:** Building on this foundation, the study introduces the *Circular Economy–Embedded Garbage Truck Vehicle Routing (CE-GTVR)* framework—a conceptual model that integrates segregation efficiency, recovery potential, and CO_2 emissions into routing logic.

These objectives frame Egypt's transition both as a national priority and as a replicable model for Gulf Cooperation Council (GCC) and Middle East and North Africa (MENA) cities, offering a transition toward *Circular Economy 2.0*.

2. Literature Review

2.1 Circular Economy Principles in Waste Management

CE reframes waste from an end-of-pipe liability into a resource cycle, where prevention, reuse, and recovery take precedence over disposal (EC 2015; Ellen MacArthur Foundation 2019). CE principles are increasingly central to climate and resource-efficiency agendas, linking waste reduction to emission mitigation (Mandpe et al. 2022). Recent studies confirm that embedding CE in waste logistics can substantially reduce landfill dependence while generating economic value streams (Kannan et al. 2024; Wiechert et al. 2025).

[1] Egypt's Vision 2030, launched in 2016, is a national sustainable development strategy aligned with the UN SDGs. It seeks to improve the quality of life through a competitive, diversified, knowledge-based economy, and a sustainable ecosystem.

In the Middle East, CE is increasingly tied to national sustainability agendas, such as Saudi Arabia's National Transformation Program, which emphasizes waste-to-resource transitions, and the UAE's CE Policy for Sustainable Waste Management, which promotes recycling industries as part of a green economy strategy (Saudi Vision 2030 2020; UAE Government of Dubai 2021). Figure 3 illustrates CE loops, highlighting the complementary roles of biological and technical cycles.

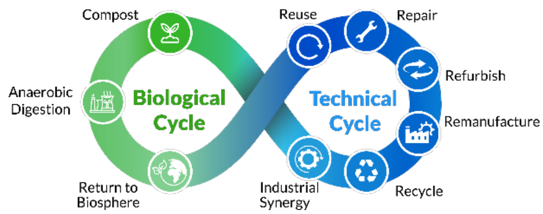

Figure 3. Circular economy loops for waste management

2.2 Smart Waste Systems and Digital Integration

Global smart cities embed CE principles through digital systems— such as RFID-based pay-as-you-throw in Seoul, mandatory three-bin separation in San Francisco, and Barcelona's open-data waste collection platform (SMG 2022; SFDOE 2020; Ajuntament de Barcelona 2021). These cases show how governance-backed digital tools drive recovery. Reviews confirm routing optimization is central to smart waste systems, cutting costs and emissions when paired with monitoring (Tirkolaee et al. 2022). Recent studies highlight AI- and IoT-driven "Waste 4.0" frameworks as efficiency benchmarks (Li et al. 2025; Mahmood et al. 2025; Wiechert et al. 2025). In the GCC, integration is emerging: Riyadh is testing RFID fleet monitoring, while Dubai's 2041 Waste Master Plan prioritizes digital routing, and Qatar's Solid Waste Management Center (SWMC) has introduced centralized waste-stream monitoring (Saudi Vision 2030 2020; UAE Government of Dubai 2021; Qatar SWMC 2020). Collectively, these initiatives demonstrate growing alignment between digital governance and CE-oriented operations. Figure 4 illustrates this architecture, linking bins, fleets, facilities, and data flows (Figure 4).

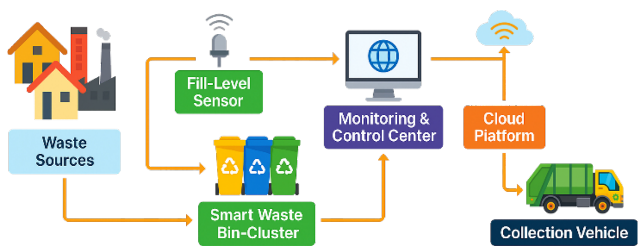

Figure 4. Integrated smart waste management system architecture

2.3 Egypt's Waste System in Context

Despite Vision 2030 and Law 202/2020, Egypt's recovery rate remains under 20%, with landfills absorbing most of the MSW (WMRA 2021; OECD 2024; Khafagy et al. 2024). Fragmented authorities and underfunded infrastructure undermine implementation. Digital tools have been piloted in Alexandria, where GIS-based route optimization has been tested but without large-scale integration into daily operations (Khafagy et al. 2024; OECD 2024). According to WMRA's 2021 report, municipal officials cite chronic underfunding and low citizen participation as key barriers, while GIZ (2022) highlights the role of informal recyclers capturing up to 80% of materials outside the formal system. The 1st objective is addressed by diagnosing Egypt's structural, financial, and operational gaps, situating its MSW system within MENA and GCC contexts to expose barriers to circular transition.

2.4 Implementation in GCC, MENA, and Egypt

GCC states have set ambitious CE targets—Saudi Arabia aims for 82% diversion by 2035 and Dubai targets near-zero landfilling by 2041, and Qatar's SWMC has advanced centralized monitoring—yet implementation remains landfill-heavy (Saudi Vision 2030 2020; Qatar SWMC 2020; UAE Government of Dubai 2021). While policy ambition is clear, operational models are scarce (Plan Bleu/UNEP-MAP 2020; UNEP & ISWA 2024). More broadly, three gaps persist across MENA MSW systems: (i) governance and technology remain misaligned, as policy alone proves insufficient (Guerrero et al. 2013; OECD 2024); (ii) financing and integration challenges undermine implementation despite bold targets (GIZ 2022; Wiechert et al. 2025); and (iii) in Egypt, no operational tools currently connect CE goals with the translation of national strategy into practice.

3. Methodology

Benchmarking is employed to assess international best practices in MSW management and their transferability to Egypt. Benchmarking is an established operations research tool for identifying performance gaps and adapting innovations (Tirkolaee et al., 2022; Kannan et al., 2024; Li et al., 2025). In sustainability contexts, it enables structured contextualization of global experiences while aligning with national reform.

3.1 Analytical Framework

The analysis applies a *five-lens framework* covering: (1) Policy and regulation, (2) Service design, (3) Infrastructure, (4) Data and operations, and (5) Social systems. This multidimensional structure, presented in Figure 5, captures the institutional, technical, and behavioral dimensions of smart waste transitions, ensuring that governance, technology, and community engagement are jointly assessed (Ellen MacArthur Foundation 2019; OECD 2024).

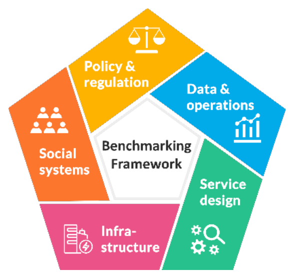

Figure 5. The five-lens benchmarking framework for smart circular waste systems

3.2 Benchmarking Process Flow

The benchmarking followed a *four-stage process*, shown in Figure 6:

1. *Literature Review*: Collection of global and national references (2015–2025).
2. *Data Extraction:* Use of standardized five-lens template (Table 1).
3. *Comparative Assessment*: Cross-case synthesis.
4. *Transferability Scoring*: Application of traffic-light rubric (Table 2) with scoring system.

Figure 6. Benchmarking process flowchart

3.3 Data Collection and Structuring

Data were drawn from peer-reviewed literature, government policies, and international reports. To ensure comparability, a standardized data extraction template (Table 1) was applied. Each lens was populated with evidence on regulations, service models, infrastructure, digital tools, and social participation. Only sources published between 2015 and 2025 were included, prioritizing recent studies, international agency reports (UNEP, OECD, EMF), and official government documents.

Table 1. Benchmarking data extraction template (Adapted from UNEP 2016; Ellen MacArthur Foundation 2013)

Lens	Data Extracted
Policy & Regulation	National/local laws and compliance mechanisms
Service Design	Collection models, frequency, and separation
Enabling Infrastructure	Fleet, bins, Material Recovery Facilities (MRFs), and treatment plants
Data & Operations	IoT, routing, monitoring, and billing systems
Social Systems	Citizen engagement and informal sector role

3.4 Case Selection

Four global cities were selected —*Seoul, San Francisco, Barcelona,* and *Singapore*—representing diverse governance models, infrastructures, and innovation trajectories. These cases were chosen based on three criteria:

- Demonstrated implementation of CE-aligned waste policies.
- Availability of performance data (diversion rates, recovery, or digital integration).
- Relevance to Egypt's urban density, infrastructure constraints, and policy ambitions.

3.5 Transferability Assessment and Scoring System

To evaluate the feasibility of adapting international practices to Egypt, a *traffic-light rubric* was applied across three dimensions, *legal, operational, and socio-economic*. Each dimension was scored on a *1–5 scale using structured anchor criteria* (Table 2), with the average score determined the classification: *Green (≥ 4.0), Amber (2.5–3.9), Red (≤ 2.4)*. This semi-quantitative approach enhances transparency and reduces subjectivity in the scoring process. Each of the three dimensions was defined with explicit anchor points. Table 3: Three-dimensional transferability scoring rubric (Adapted from UN Environment, 2016; Ellen MacArthur Foundation, 2013; GIZ, 2023) details the *three-dimensional scoring rubric* used to guide assessments.

Table 2. Trafic-light rubric assessment (Adapted from UN Environment 2016; Ellen MacArthur Foundation 2013; GIZ 2023)

Classification	Legal Fit	Operational Fit	Socio-economic Fit
Green (high feasibility, near-term pilot)	Fully aligned with Law 202/2020 and Vision 2030	Feasible with existing fleets/facilities	Broad citizen acceptance and informal sector integration
Amber (medium feasibility, conditional)	Requires minor regulatory adjustments	Needs incremental upgrades (fleets/bins/ICT)	Requires financing or behavioral change
Red (low feasibility, long-term)	Not currently supported by legislation	Major infrastructure investment required	Low likelihood of acceptance without systemic reform

Table 3. Three-dimensional transferability scoring rubric (Adapted from UN Environment, 2016; Ellen MacArthur Foundation, 2013; GIZ, 2023)

Score	Legal Fit	Operational Fit	Socio-economic Fit
1	No supporting legislation and conflicts with policies	Not feasible with current fleets/ICT and full overhaul needed	Strong resistance, unaffordable and no precedent
2	Weak or outdated framework and major reforms required	Very limited and only donor-funded pilots viable	Major affordability/acceptance barriers and resistance likely
3	Partially compatible with Law 202/2020 and decrees/enforcement needed	Moderately feasible with fleet/ICT upgrades	Mixed acceptance and needs subsidies and awareness campaigns
4	Mostly aligned with Law 202/2020 & Vision 2030; stronger enforcement needed	Feasible in major cities with minor adjustments (training/O&M)	Generally acceptable with safeguards and communication
5	Fully aligned with law and strategy	Immediately feasible and scalable with minimal changes	Widely acceptable and culturally/economically aligned

To test robustness, each score was perturbed by ±1 point while keeping other dimensions constant. This process highlights which factors most strongly influence classification outcomes and ensures results are not overly dependent on single-value judgments (Guerrero et al., 2013; OECD, 2024). For example, *Barcelona* averaged *3.7 (Amber–Green)*. Reducing operational feasibility to 3 shifted the average to *3.3 (Amber)*, while increasing socio-economic fit to 4 raised the average to *4.0 (Green)*. Thus, Barcelona's classification shows *medium stability*, oscillating between Amber and Green depending on financing and technical capacity. Embedding stability in transferability results improves scoring clarity and conciseness.

3.6 Methodological Validation

Although semi-qualitative, the scoring framework improves reproducibility compared to purely qualitative benchmarking. Future validation should apply structured consensus methods such as Delphi expert panels or multi-criteria decision analysis (MCDA), to test score consistency and quantify trade-offs between policy feasibility, social readiness, and infrastructural requirements (Cinelli et al., 2020; Vasconcelos et al., 2022). To enhance rigor, the rubric was cross-checked with evidence from Alexandria's emerging digital initiatives (WMRA, 2021), national reform pilots supported by GIZ (2022), and external policy reviews (OECD, 2024). These triangulations yielded consistent Green–Amber classifications, suggesting indicative reliability of the scoring system.

4. Global Benchmarking

Benchmarking four international cities highlight how policy and innovation deliver tangible results, and what Egypt can realistically adapt under its own economic and social constraints.

- *Seoul* pioneered *Pay-As-You-Throw (PAYT)* systems with more than 6,000 RFID-enabled bins linked to billing platforms, cutting food waste by *31–47%* through composting and AD (Roy et al. 2022).
- *San Francisco* enforces *zero-waste ordinances* with mandatory three-bin separation, performance-linked contracts, and audits. Diversion rates exceed 80% (Wilson et al. 2006; Guerrero et al. 2013).
- *Barcelona* integrates semi-underground IoT bins with the *Sentilo open-data platform*, improving routing efficiency and public trust (Ajuntament de Barcelona 2021).
- *Singapore* mandates *Pneumatic Waste Conveyance Systems (PWCS)* in new developments, monitored by the National Environment Agency (NEA 2023).

Table 4 consolidates case characteristics, while Table 5 applies the *traffic-light rubric scoring* that situates Egypt's performance against CE benchmarks. Table 6 quantifies the performance gap by comparing Alexandria's current MSW indicators with those of the benchmarked cities. The 2nd objective is addressed by benchmarking four global smart waste systems—Seoul, San Francisco, Barcelona, and Singapore—through a five-lens framework that highlights transferable practices for Egypt

Table 4. Comparative benchmarking of four international smart waste systems (Adapted from Roy et al., 2022; Wilson et al., 2006; Ajuntament de Barcelona, 2021; NEA, 2023)

Dimension	Seoul	San Francisco	Barcelona	Singapore
Policy and Regulation	National PAYT legislation	Zero-waste ordinance; franchise KPIs[2]	Smart city strategy; open-data governance	Building codes mandate PWCS
Service Design	RFID-enabled bins; prepaid bags	Mandatory three-bin separation	IoT-enabled bins; semi-underground containers	Automated pneumatic collection
Infrastructure	> 6,000 RFID bins; composting & AD plants	Composting and recycling facilities	IoT gateways; semi-underground stations	> 40 PWCS installations;
Data and Operations	Real-time telemetry linked to billing	Performance audits tied to contracts	Sentilo open-data platform; KPI dashboards	NEA centralized monitoring system
Social Systems	Awareness campaigns; compliance monitoring	Strong civic culture; NGO[3] partnerships	Transparency via open data; community pilots	Hygiene campaigns; modernity branding
Reported Outcomes	31–47% reduction in food waste	Diversion rate >80%	Reduced costs and CO_2 emissions	Cleaner streets; higher recyclables capture

Table 5. Transferability of international models to Egypt (scored rubric) (Adapted from Roy et al., 2022; Wilson et al., 2006; Ajuntament de Barcelona, 2021; NEA, 2023)

Dimension	Seoul	San Francisco	Barcelona	Singapore
Legal Fit	5	3	4	1
Operational Fit	4	3	4	2
Socio-economic Fit	3	3	3	3
Average Score	**4.0**	**3.0**	**3.7**	**2.0**
Classification	Green	Amber	Amber	Red
Stability	**High** unless socio-economic readiness drops	**Medium** sensitive to legal enforcement reforms	**Medium** oscillates depending on financing/technical capacity	**Low** unless major legal and infrastructure reforms occur

[2] KPI's: Key Performance Indicators.
[3] NCO: Non-Governmental Organization.

Seoul's PAYT is legally aligned with Law 02/2020 and feasible in dense districts like Alexandria, the model scores Green overall but requires affordability measures for public acceptance. In Egypt, the absence of binding ordinances reduces transferability of San Francisco's 3-bin system, yielding an *Amber* score—mainly for institutions and hotels. The same applies to Barcelona's system, where it is more suitable for touristic areas. While Singapore's PWCS is effective, high capital cost and regulatory gaps in Egypt keep it at *Red*, with limited applicability to new cities. Yet, it will be taken into further consideration to reflect future potential in new urban developments across Egypt, GCC, and MENA. If embedded into infrastructure planning and supported by legal enforcement, the model could represent a major step toward smart-city alignment and sustainability (Table 6).

Table 6. Egypt's alignment with Circular Economy principles compared to International Benchmarks (Adapted from OECD 2024; GIZ 2022; SFDOE 2020; Ajuntament de Barcelona 2021; NEA 2023; SMG 2022; Khafagy et al. 2024)

CE Principle	Benchmark Example	Egypt's Status	Alignment
Waste prevention & reduction	Seoul PAYT	No PAYT	Low
Material circulation	San Francisco > 80%, Barcelona 58%	< 20% recovery; weak separation	Low–Medium
Energy recovery	Singapore WtE[4]/PWCS	> 70% landfill; minimal capture	Low
Informal sector integration	San Francisco NGO partnerships Barcelona community participation	Informal recycling up to 80%, excluded	Medium
Digital & smart systems	Seoul RFID; BCN IoT	GIS pilots in Alexandria, Port Said	Medium

Egypt's circular transition hinges on embedding global benchmarks within the local context. Fiscal constraints remain severe —tariffs cover < 40% of service costs (OECD 2024)—while fragmented undermines enforcement (GIZ 2022). Yet, Law 202/2020, informal sector recovery, and potential climate finance provide strong enablers (UNEP and ISWA, 2024; Khafagy et al. 2024). Aligning global benchmarks with these national dynamics underscores the need for phased pilots that leverage enablers while managing fiscal and social risks. An approach that sets the stage for Egypt's adaptation strategy is discussed next.

5. National Adaptation Strategy and Alexandria as a Pilot

Alexandria, Egypt's second-largest city and a key coastal hub, illustrates both the urgency of reform and the potential for a circular transition. Seasonal surges in tourism and population mobility increase MSW by more than 10%, pushing daily volumes above 5,000 tons during peak summer months (Elgazzar et al. 2017; GIS SWM Alexandria 2025). Over 70% of the city's collection fleet is beyond service life, causing frequent breakdowns and unreliable coverage. In addition, seasonal MSW fluctuations reinforce the need for smart-bin integration, dynamic routing, and pilot interventions positioning Alexandria as an ideal testing ground for scalable reforms. To further highlight Egypt's relative position, Table 7 contrasts Alexandria's current MSW indicators with those of the benchmarked cities, quantifying the performance gap that underpins the adaptation strategy.

Table 7. Comparative performance: Alexandria vs. international benchmarks (Adopted from WMRA 2021; Roy et al. 2022; CAPMAS 2022; Khafagy et al. 2024; Elgazzar et al. 2017; Wilson et al. 2006; Ajuntament de Barcelona 2021; NEA 2023)

Indicator	Alexandria	Seoul	San Francisco	Barcelona	Singapore
MSW generation (tons/day)	~ 5,000 peak	~ 12,000	~ 2,000	~ 3,500	~ 8,000
Collection coverage	60–65%	> 95%	> 95%	> 90%	> 95%
Diversion/recovery rate (%)	< 20%	31–47% food waste diversion	> 80%	58%	> 60% recyclables; PWCS in new builds
Landfill share (%)	> 70%	< 20%	< 20%	~ 40%	< 10%
Digital integration	Limited GIS pilots (Alexandria, Port Said)	RFID PAYT system (6,000+ bins)	Contract-linked KPIs & audits	IoT & open-data platform (Sentilo)	Centralized PWCS monitoring
Fleet condition	> 70% beyond service life	Modernized, RFID-enabled	Public-private fleet, upgraded	IoT-enabled routing	Automated pneumatic transfer

[4] WtE: Waste to Energy.

Benchmarking against global cities confirms that Egypt's MSW system is only partially aligned with CE principles. Closing gaps requires a phased, context-sensitive strategy that sequences reforms by feasibility. Using the traffic-light rubric (UNEP 2016; OECD 2024; GIZ 2022), reforms are clustered into near-term (green), medium-term (amber), and long-term (red) actions Figure 7. This sequencing reflects governance capacity, financing constraints, and Vision 2030 priorities, while positioning Alexandria as the pilot zone for early reforms.

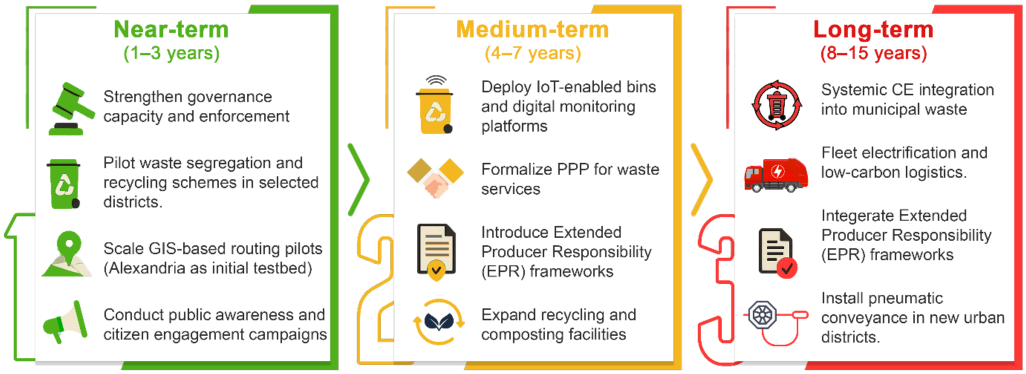

Figure 7. Phased adaptation strategy for Egypt's transition to a smart circular waste system

5.1 Near-Term Priorities (Green, 1–3 years)

Immediate measures should focus on low-cost, high-impact interventions that deliver visible improvements in Alexandria before scaling elsewhere. These measures include:

- Governance strengthening through performance-based contracts between WMRA and governorates.
- Segregation-at-source pilots in Alexandria (and other cities), supported by household and school-level awareness campaigns.
- GIS-based fleet routing to reduce fuel consumption and improve service reliability (OECD 2024).
- Community outreach via civil society–co-designed programs, applying participatory models (Vasconcelos et al. 2022).

5.2 Medium-Term Reforms (Amber, 4–7 years)

Once pilots demonstrate viability, reforms can expand to require institutional and financial restructuring, such as:

- IoT-enabled monitoring platforms modeled after Seoul's RFID bins and Barcelona's open-data systems (SMG 2022; Ajuntament de Barcelona 2021).
- Decentralized recycling and composting hubs near peri-urban areas to absorb seasonal peaks (GIZ 2022).
- Tariff and incentive reforms, including recycling credits and user fee adjustments, to achieve cost recovery.

5.3 Long-Term Transformations (Red, 8–15 years)

Capital-intensive reforms will shape the system's long-term sustainability and climate alignment, including:

- Electrification of the collection fleet, with potential to reduce emissions by 30–40% (Khafagy et al. 2024).
- PWCS in new high-density districts, modeled on Singapore (NEA 2023).
- Waste-to-Energy (WtE) plants integrated with district heating and power networks, contributing to climate targets (Salem et al. 2022; OECD 2024).

Alexandria emerges as a testbed for near-term pilots, illustrating the convergence of governance, technology, and community participation. Lessons from these pilots would then be fed into medium- and long-term reforms, setting Egypt on a pathway toward a smart, circular waste system aligned with Vision 2030 and the Sustainable Development Goals. This phased roadmap addresses the 3rd objective of the study by clustering reforms into near-, medium-, and long-term actions aligned with Vision 2030 and SDGs.

6. Future Pathways

Benchmarking and phased adaptation confirm that Egypt's MSW transition depends on embedding CE indicators into operations. Conventional VRP models—capacitated, periodic, or stochastic—optimize cost, time, or distance but rarely integrate recovery, segregation, or environmental metrics (Hannan et al. 2018; Mahmood et al. 2025). Even advanced variants like DVRP and Multi-Compartment VRP only partly address flexibility and multi-stream handling. Reviews confirm routing optimization improves efficiency and environmental outcomes but note limited integration with policy or circularity metrics (Tirkolaee et al. 2022). To address this issue, the proposed *Circular Economy–Embedded Garbage Truck Vehicle Routing (CE-GTVR)* lays the foundation for *Circular Economy 2.0* by embedding CE indicators—segregation efficiency, recovery potential, CO_2 per ton, and compliance with Law 202/2020—into routing decisions (Kannan et al., 2024; OECD, 2024).

Figure 8 illustrates this shift, with sensor-enabled bins, segregation triggers, and policy rules feeding a centralized optimization engine. Recent VRP research has advanced *Green VRP* (emission minimization), *Reverse Logistics VRP* (secondary material recovery), *Multi-objective VRP* (balancing cost, time, and emissions), and *AI-enhanced DVRP* (real-time adaptability under uncertainty) (Tirkolaee et al. 2022; Mahmood et al. 2025; Li et al. 2025). More recent multi-objective formulations consider sustainability trade-offs (Li et al. 2025), yet few embed CE-specific metrics or regulatory compliance. CE-GTVR extends this frontier by aligning optimization with Vision 2030 and integrating segregation and recovery KPIs into daily routing. Table 8 illustrate how Alexandria's recovery could increase from < 20% to 45–50%**,** while CO_2 emissions/ton could fall by 25–30% % under CE-GTVR scenarios.

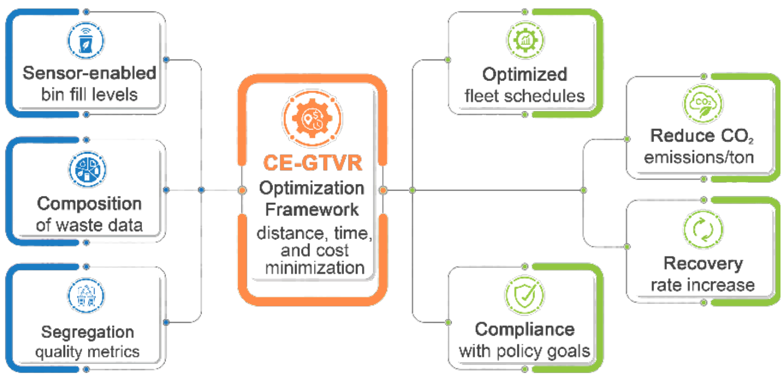

Figure 8. Conceptual schematic of the Circular Economy–Embedded Garbage Truck Vehicle Routing (CE-GTVR)

Table 8. Scenario illustration of CE-GTVR gains in Alexandria (Adapted from WMRA 2021; CAPMAS 2022; Khafagy et al. 2024; OECD 2024)

Scenario	Collection Coverage (%)	Recovery Rate (%)	CO_2 per ton (kg)
Current	60–65	< 20	~ 120
With CE-GTVR (projected)	> 85	45–50	< 90

6.1 Comparative Positioning of CE-GTVR

Table 9 contrasts VRP variants by their alignment with CE priorities. CE-GTVR uniquely incorporates policy constraints and circular KPIs—making it both stream-specific and compliance-driven.

Table 9. VRP variants and their alignment with circular economy goals (Adapted from Li et al. 2025; Roy et al. 2022; Mahmood et al. 2025; Hannan et al. 2018; proposed CE-GTV framework)

VRP Variant	Optimization Focus	Application in Waste Management	Adaptability to CE Goals	Stream Sensitivity	Environmental KPIs Embedded	Policy Alignment
Capacitated VRP (CVRP)	Minimize cost/distance or vehicle capacity	Prevents truck overloading	Not adaptable	One-size routing	None	Not aligned
VRP with Time Windows	Time-constrained routing	Restricted urban districts	Partial	Time zones only	None	Not aligned
Periodic VRP (PVRP)	Multi-day service cycles	Alternating organic/residual schedules	Partial	Generic cycles	None	Not aligned
Dynamic VRP (DVRP)	Real-time, dynamic routing	IoT-enabled bins; fill-level–triggered routing	Conditional if sensor-linked	Generic triggers	Limited (if coupled)	Needs adaptation

VRP Variant	Optimization Focus	Application in Waste Management	Adaptability to CE Goals	Stream Sensitivity	Environmental KPIs Embedded	Policy Alignment
Multi-Depot VRP (MDVRP)	Multi-depot routing	Large metropolitan areas	Structural flexibility	Not stream-specific	None	Not aligned
Stochastic VRP (SVRP)	Demand/traffic uncertainty	High-variability urban contexts	Useful for resilience	Not stream-specific	None	Not aligned
Multi-compartment VRP	Segregated compartments	Simultaneous collection of recyclables and organics	Partial	Basic segregation	None	Weak alignment
CE-GTVR (proposed)	**Multicriteria: cost, recovery, CO_2, purity**	**Stream-specific, policy-aligned waste collection**	**Fully embedded**	**Stream-specific triggers**	**Built-in (CO_2, purity, recovery)**	**CE-aligned with Vision 2030**

6.2 Future Research Directions
Future pathways focus on piloting CE-GTVR in Alexandria, as proof of concept. The 4th objective is addressed by introducing CE-GTVR as a conceptual framework that embeds CE indicators into daily routing, extending conventional VRP towards Circular Economy 2.0. To implement the proposed CE-GTVR framework, three priorities are planned:

1. **Modeling and Simulation:** Integrate CE indicators into optimization logic (Li et al., 2025).
2. **Pilot Testing:** Deploy in Alexandria using GIS and seasonal data (Khafagy et al. 2024; OECD 2024).
3. **Benchmarking Studies:** Compare CE-GTVR to legacy VRPs across cost, CO_2, and recovery performance.

7. Validation and Limitations
The methodology followed in this work offers a conceptual validation of Egypt's MSW transition by triangulating international benchmarks with national policies and infrastructure. However, three key limitations remain:

1. **Qualitative Benchmarking:** The traffic-light rubric has not been statistically tested, limiting robustness. Future validation through Delphi panels, MCDA or Failure Mode and Effect Analysis (FMEA) scoring would enhance reliability (Cinelli et al., 2020; Vasconcelos et al., 2022). This design follows established benchmarking approaches emphasizing structured scoring and comparability (Tirkolaee et al., 2022). The framework provides *conceptual validation* by triangulating benchmarks against Egypt's legal and infrastructural context. However, the study remains mainly qualitative.
2. **Conceptual CE-GTVR Framework:** The *Circular Economy–Embedded Garbage Truck Vehicle Routing (CE-GTVR)* framework remains theoretical. While it advances routing by embedding CE metrics, this study does not provide simulation or algorithmic modeling. Future research should integrate segregation efficiency, recovery rates, and CO_2 per ton into optimization logic (Hannan et al., 2018; Roy et al., 2022).
3. **Limited Case Scope:** Benchmarking is restricted in coverage- covering only four cities- and expanding the range of cases would provide broader cross-regional insights and strengthen generalizability.

Additionally, simulation of CE-GTVR using Alexandria's seasonal waste data could test routing performance and quantify CE gains. While benchmarking and scoring provide conceptual validation, uncertainties remain. Social acceptance of PAYT, financing mechanisms for IoT integration, and enforcement of Law 202/2020 cannot be fully validated qualitatively. Future empirical trials, simulation modeling, and require stakeholder consensus methods.

8. Conclusion
Waste management in Egypt faces persistent challenges of rising volumes, fragmented governance, and low recovery, making the transition toward circular economy practices both urgent and complex. This study set out to benchmark international smart waste models, diagnose Egypt's system constraints, propose a phased adaptation roadmap, and introduce a future-oriented routing framework. *To achieve this, the study applied three different frameworks to evaluate the applicability of international models to the Egyptian context.* First, through a five-lens benchmarking framework, the paper identified transferable global practices from Seoul, San Francisco, Barcelona, and Singapore, thereby addressing the research gap in comparative evidence for Egypt. Second, the development of a *traffic-light adaptation roadmap* to translate these practices into a phased national strategy, directly aligned with Vision 2030 and Law 202/2020. Third, the introduction of the *Circular Economy–Embedded Garbage Truck Vehicle Routing (CE-GTVR)* as a basis for *Circular Economy 2.0* established a novel conceptual contribution that extends conventional VRP models to embed circularity indicators into daily operations.

Looking ahead, future research will focus on quantitative validation of the CE-GTVR framework through simulation pilots in Alexandria, embedding segregation efficiency, recovery potential, and CO_2 metrics into optimization models to demonstrate measurable CE gains. Future validation should apply Delphi consensus, multi-criteria decision analysis, or simulation modeling to test robustness (Cinelli et al. 2020; Vasconcelos et al. 2022).

References

Abdel-Shafy, H. I. and Mansour, M. S., Solid waste issue: Sources, composition, disposal, recycling, and valorization, *Egyptian Journal of Petroleum*, vol. 27, no. 4, pp. 1275–1290, 2018.

Abdallah, M., Talib, M. A., Feroz, S., Nasir, Q., Abdalla, H. and Mahfood, B., Artificial intelligence applications in solid waste management: A systematic research review, *Waste Management*, vol. 109, pp. 231–246, 2020.

Ajuntament de Barcelona, *Barcelona zero waste plan 2021–2027: Executive summary*, Barcelona City Council, Barcelona, 2021. Available: https://bcnroc.ajuntament.barcelona.cat/handle/11703/120701

CAPMAS, *Press release: Environmental statistics 2021*, Central Agency for Public Mobilization and Statistics, Cairo, 2022. Available: https://www.capmas.gov.eg

Cinelli, M., Coles, S. R., and Kirwan, K. Analysis of the robustness of multi-criteria decision analysis methods for sustainability assessment. *Journal of Cleaner Production*, 259, 120874, 2020.

El-Gazzar, R. F., and El-Gohary, M. A. Understanding the dilemma of the municipal solid waste management system in Alexandria, Egypt: Could ICT improve the system? In *Proceedings of the IFIP International Conference on Information and Communication Technologies for Development (ICT4D 2017)*, IFIP AICT, vol. 504, pp. 816–822. Springer, Cham, Switzerland, 2017.

Ellen MacArthur Foundation, *Towards the circular economy, vol. 1: An economic and business rationale for an accelerated transition*, Cowes: EMF, 2013. Available: https://ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1

Ellen MacArthur Foundation, *Completing the picture: How the circular economy tackles climate change*, London: EMF, 2019. Available: https://ellenmacarthurfoundation.org/completing-the-picture

European Commission, *Closing the loop: An EU action plan for the circular economy*, Brussels: EC, 2015. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614

European Commission, *Circular economy action plan: For a cleaner and more competitive Europe*, Brussels: EC, 2020. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0098

GIZ, *Improving solid waste management in Egypt*, Deutsche Gesellschaft für Internationale Zusammenarbeit, Cairo, 2022. Available: https://www.giz.de/en/worldwide/20067.html

GIZ, *Solid waste management in the context of a circular economy in the MENA region*, Deutsche Gesellschaft für Internationale Zusammenarbeit, Eschborn, 2023. Available: https://greentechknowledgehub.de/resource/solid-waste-management-context-circular-economy-mena

Guerrero, L. A., Maas, G. and Hogland, W., Solid waste management challenges for cities in developing countries, *Waste Management*, vol. 33, no. 1, pp. 220–232, 2013.

Hannan, M., Akhtar, M., Begum, R. and Basri, H., Capacitated Vehicle-Routing Problem Model for Scheduled Solid Waste Collection and Route Optimization Using PSO Algorithm, *Waste Management*, vol. 71, pp. 31–41, 2018.

Kannan, D., Khademolqorani, S., Janatyan, N. and Alavi, S., Smart waste management 4.0: The transition from a systematic review to an integrated framework, *Waste Management*, vol. 174, pp. 1–14, 2024.

Khafagy, M., Sammak, A. and Emara, K., Modeling of Methane Emissions from Waste Disposal Sites at Selected Egyptian Governorates and Potential Energy Production from Waste-to-Energy Projects, *Scientific Reports*, vol. 14, p. 25040, 2024.

Li, W., Ng, T. F., Ibrahim, H. and Wang, S. L., A literature review of the state of the art of sustainable waste collection and vehicle routing problem, *Journal of the Air & Waste Management Association*, vol. 75, no. 1, pp. 3–26, 2025.

Li, W., Wang, P., Xu, Y., Pan, L., Nie, C., & Yang, B., "Multi-Objective Optimization of Municipal Solid Waste Collection Based on Adaptive Large Neighborhood Search," *Electronics*, vol. 14, no. 1, p. 103, 2025.

Mahmood, I., Qayyum, A., Hasan, M. M., and Pradhan, B., "IoT-Enabled Smart Waste Management: A Review on Real-Time Monitoring and Route Optimization," Waste Management, vol. 157, pp. 85–101, 2025.

Mandpe, A., Paliya, S., Gedam, V. V., Patel, S., Tyagi, L. and Kumar, S., Circular economy approach for sustainable solid waste management: A developing economy perspective, *Waste Management & Research*, vol. 41, no. 3, pp. 499–511, 2022.

National Environment Agency (NEA), *Environmental services industry transformation map 2025*, Singapore: NEA, 2023. Available: https://www.nea.gov.sg/media/news

OECD, *Green growth policy review of Egypt*, Paris: OECD Publishing, 2024, doi: 10.1787/9789264478921-en.
Plan Bleu / UNEP-MAP, *State of the environment and development in the Mediterranean*, UNEP-MAP, Athens, 2020. Available: https://planbleu.org/publications/soed-2020
Qatar Solid Waste Management Center, *National waste management strategy reports*, Ministry of Municipality and Environment, Doha, 2020. Available: https://www.mme.gov.qa/QatarMasterPlan
Roy, A., Manna, A., Kim, J. and Moon, I., IoT-based smart bin allocation and vehicle routing in solid waste management: A case study in South Korea, *Computers & Industrial Engineering*, vol. 171, p. 108457, 2022.
Salem, M. E., Refky, A., Abd El-Halim, H., Nassar, I. A., Potential of waste-to-energy conversion in Egypt, Journal *of Electrical and Computer Engineering*, 2022, Article ID 7265553.
San Francisco Department of the Environment (SFDOE), *Zero waste roadmap: Progress report 2010–2020*, San Francisco: City and County of San Francisco, 2020. Available: https://sfenvironment.org/zero-waste
Saudi Vision 2030, *National Transformation Program: Waste management and circular economy targets*, Government of Saudi Arabia, Riyadh, 2020. Available: https://vision2030.gov.sa
Seoul Metropolitan Government (SMG), *Policy brief: Food waste reduction through PAYT and RFID integration*, UNDP Seoul Policy Center, Seoul, 2022. Available: https://www.undp.org/policy-centre/seoul
Tirkolaee, E. B., Alinaghian, M., Khalili-Damghani, K., Soltani, M., and Ghaffarian, S., A Novel Model for Sustainable Waste Collection Arc Routing, *Computers & Industrial Engineering*, vol. 163, p. 107804, 2022.
UAE Government of Dubai, *Dubai integrated waste management master plan 2021–2041*, Government of Dubai, Dubai, 2021. Available: https://u.ae/en/information-and-services/environment-and-energy/waste-management
UNEP, *Frontiers 2016: Emerging issues of environmental concern*, Nairobi: United Nations Environment Programme, 2016. Available: https://www.unep.org/resources/frontiers-2016
UNEP and ISWA, *Global waste management outlook 2024*, Nairobi: United Nations Environment Programme and International Solid Waste Association, 2024. Available: https://www.unep.org/resources/report/global-waste-management-outlook-2024
Vasconcelos, L. T., Silva, F. Z., Ferreira, F. G., Martinho, G., Pires, A. and Ferreira, J. C., Collaborative process design for waste management: Co-constructing strategies with stakeholders, *Environment, Development and Sustainability*, vol. 24, pp. 9243–9259, 2022.
Wiechert, M., Aboulfotouh, A. and Roushdy, Y., Extended Sector Responsibility—The Tourism Sector as a Driver for Improved Waste Management in Egypt, Morocco and Tunisia, *Recycling*, vol. 10, no. 2, p. 29, 2025.
WMRA, *Annual performance report of the Waste Management Regulatory Authority*, Ministry of Environment, Cairo, 2021. Available: https://www.eeaa.gov.eg
Wilson, D., Velis, C. and Cheeseman, C., Role of informal sector recycling in waste management in developing countries, *Habitat International*, vol. 30, no. 4, pp. 797–808, 2006.
World Bank, *What a waste 2.0: A global snapshot of solid waste management to 2050*, Washington DC: World Bank, 2018. Available: https://openknowledge.worldbank.org/handle/10986/30317

Biographies

Ghada M. A. Younes is a researcher in sustainable waste management, CE transitions, and industrial engineering applications. She holds a B.Sc. in Architectural Engineering from the Faculty of Engineering, Alexandria University and a postgraduate Multimedia diploma from the Information Technology Institute (ITI). Ghada is completing her master's research at the Faculty of Engineering, Alexandria University, titled *Embedding Circular Economy Principles in Garbage Truck Routing: A Smart Approach to Waste Management*. She also serves as a faculty at the Arab Academy for Science, Technology, and Maritime Transport (AASTMT) and contributes to national initiatives advancing technical and vocational excellence.

Reem Al-Kadeem is a Professor of Industrial Engineering and Head of the Production Engineering Department at Alexandria University. She is one of the founders of the Arabian Ergonomics Society, an under-registration society and a subdivision of the International Ergonomics Association in the Middle East (IEA). She is the founder of the only Ergonomics/Human Factors Laboratory in Alexandria University. She earned a B.Sc. in Production Engineering and an MSc degree in Ergonomics, both from Alexandria University. She completed her PhD degree in Biomechanics as a channel system PhD student between Alexandria University, Egypt and Miami University, USA. Her research interests are ergonomics and macro ergonomics, industrial management, organizational management, and usability.

Nermine Harraz is a Professor of Industrial Engineering in Alexandria University, Egypt. She is experienced in working with industry through research. Professor Harraz has more than 50 papers in supply chain and logistics, facilities planning, and health care management. She supervised many M.Sc. and Ph.D. thesis in the field of Industrial engineering. Professor Harraz is serving in many administrative positions in higher education institutions especially in managing the international student's bureau, community service units and technology transfer.

Ahmad E. Elhabashy received his Ph.D. degree in Industrial and Systems Engineering from Virginia Tech, USA, in 2018, and both his B.Sc. and M.Sc. degrees in Production Engineering from Alexandria University, Egypt, in 2009 and 2012, respectively. Ahmad is currently working at the Production Engineering Department at Alexandria University. His research interests include quality control, production planning and control, modelling of industrial systems, and optimization, particularly in the manufacturing context.