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GOVERNING CIRCULAR AND DIGITAL TRANSITIONS IN MUNICIPAL SOLID WASTE MANAGEMENT

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Abstract

Municipal solid waste management (MSWM) in low- and middle-income settings is increasingly framed through circular economy, digitalization, and climate-resilience agendas. Yet the effectiveness of these approaches depends on basic service reliability, material quality, institutional capacity, finance, markets, and social legitimacy. This integrative review updates a 2024 synthesis of Asian and African MSWM using 354 supplied Scopus records indexed for 2024–2026. Evidence was coded from bibliographic metadata, titles, abstracts, and keywords across six domains and interpreted through three tensions: aspiration versus service reality, data-rich optimization versus data-poor institutions, and aggregate efficiency versus distributive justice. Because full texts and the complete search log were unavailable, the review does not estimate pooled effects, rank technologies universally, or treat author-developed propositions as validated transition pathways. The literature indicates that prevention, segregation, logistics optimization, biological and thermal recovery, digital decision support, and engineered disposal can contribute to improved outcomes when their enabling conditions are met. Across domains, weak collection coverage, contaminated feedstock, fragmented authority, precarious informal work, volatile markets, and limited monitoring constrain implementation. We therefore propose—not empirically validate—a context-conditioned framework linking service foundations, governance, life-cycle finance, inclusion, data readiness, and technology portfolios. The framework positions digital tools as decision infrastructure rather than substitutes for service capacity and treats justice and residual control as performance criteria. Priority research needs include reproducible search protocols, design-specific quality appraisal, closed mass balances, longitudinal implementation studies, distributional indicators, and climate-stress testing. The review supports cautious, sequenced adaptation while identifying where evidence remains insufficient for firm policy prescriptions.

Keywords: municipal solid waste management; circular economy; digital waste systems; environmental governance; waste valorization; environmental justice; developing regions

INTRODUCTION

Municipal solid waste management (MSWM) has become a defining test of urban governance in rapidly changing low- and middle-income settings. Population growth, consumption change, settlement expansion, and diversification of material use increase both the quantity and complexity of waste, while public institutions frequently operate with incomplete data, constrained budgets, uneven collection coverage, and weak enforcement. The baseline review by Zhang et al. (2024) demonstrated that the visible symptoms—open dumping, open burning, deficient collection, unmanaged landfills, and low recycling—are produced by intertwined socioeconomic, infrastructural, and cultural barriers rather than by a single technical deficit. Recent scholarship sharpens that conclusion. It depicts waste systems as socio-technical and political systems in which material flows, service rights, markets, behavior, land use, technology, and institutional authority must be coordinated (Fong & Omar, 2025; Dharmanu Yudartha & Yuwono, 2026; Gajera & Henrysson, 2026).

The literature published or indexed after the baseline review also changes the vocabulary of the field. Circular economy, zero-waste cities, artificial intelligence, digital twins, life-cycle thinking, extended producer responsibility, energy justice, and resilience now sit alongside established concerns about collection, treatment, and disposal. This expansion is intellectually productive, but it creates a risk of solutionism. A city can procure sensors without dependable collection, announce circularity without verified mass balances, or select a waste-to-energy

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plant without reliable feedstock and pollution controls. Recent evidence repeatedly shows that technology readiness is conditional on institutional readiness, and that technically attractive pathways can reproduce inequality when costs, risks, and benefits are distributed unfairly (Tahulela & Hashemi, 2026; Kubanza & Koenaite, 2026; Shekari et al., 2025).

This review asks four questions. First, what substantive advances does the recent literature add to the baseline diagnosis of MSWM challenges in developing regions? Second, which combinations of governance, finance, participation, infrastructure, and technology are associated with plausible transitions away from uncontrolled disposal? Third, where do digitalization, spatial analysis, and life-cycle assessment improve decisions, and where do they merely optimize incomplete systems? Fourth, what research designs and policy sequences can connect household practice to measurable recovery, emissions reduction, public health protection, and landfill diversion?

The article contributes an updated synthesis rather than claiming a new general theory. It places established integrated solid waste management (ISWM), circular-economy, socio-technical, and institutional perspectives in a single decision frame and makes the boundary conditions of technology choice explicit. Throughout this article, "developing regions" is used pragmatically for the low- and middle-income and Global South settings represented in the baseline review and update corpus; it is not treated as a homogeneous analytical category. Regional observations are illustrative unless the underlying records support broader inference.

REVIEW DESIGN, EVIDENCE APPRAISAL, AND REPRODUCIBILITY BOUNDARIES

Evidence sources and scope. This integrative review combines the 2024 Science of the Total Environment review by Zhang et al., which synthesized 170 studies on Asian and African MSWM published during 2013–2023, with an update corpus of 354 Scopus records supplied as a bibliographic export. The manuscript source reports 352 unique DOI identifiers and a concentration of records in 2025–2026, with a smaller 2024 group and one record assigned to 2027. No sources outside the supplied evidence package were added.

Eligibility and coding. Update records were assessed from bibliographic metadata, titles, abstracts, and author keywords. Records were included in the narrative synthesis when those fields addressed municipal solid waste systems, their environmental or health consequences, governance, financing, social participation, spatial or digital decision support, or recovery and disposal technologies. Evidence was coded into six analytical domains: prevention and source segregation; collection, transport, and spatial planning; biological, thermal, and material recovery; landfill, pollution, and health; governance, finance, participation, and justice; and data, digitalization, and decision support. A record could inform more than one domain when its abstract supported cross-domain interpretation.

Evidence appraisal and synthesis rules. Study designs were not treated as interchangeable. Review-level syntheses were used to identify recurring themes; observational and qualitative studies to interpret context and implementation; life-cycle, techno-economic, GIS, and optimization studies to identify scenario-dependent trade-offs; and laboratory or process studies to assess technical potential under bounded conditions. Confidence in a claim was considered higher when multiple designs converged, boundary conditions were explicit, and the claim remained at the resolution reported in the abstract. Model outputs were not treated as observed operational performance, and isolated cases were not generalized to whole regions. Apparent disagreement was retained when studies used different system boundaries, functional units, settings, or outcome definitions.

The counts of 354 records and 352 unique DOI identifiers are descriptive figures carried in the available manuscript, not independently reproducible screening results. The 2027-assigned record is not treated as evidence published within the 2024–2026 update window. No numeric geographic stratification or publication-status verification is possible from the reported extraction. Consequently, examples outside lower- and middle-income settings serve as contextual comparisons, not direct evidence of transferability.

Reproducibility boundary. The supplied manuscript does not preserve the complete Scopus query, search date, searched fields, non-DOI duplicate log, screening decisions, reasons for exclusion, number of reviewers, conflict-resolution process, or a study-level quality-assessment file. These details cannot be reconstructed reliably and are therefore reported as unavailable rather than inferred. Figure 1 distinguishes documented information from unavailable elements. A submission-ready systematic update should append the original search log, a PRISMA-style flow diagram, the extraction codebook, and independent-screening records.

The abstract-level evidence base also limits appraisal of sampling, measurement validity, model equations, inventories, confounding, and risk of bias. Accordingly, the appraisal matrix in Table 1 is an interpretive confidence framework, not a formal study-level risk-of-bias assessment. Claims concerning feasibility, fiscal exposure, market viability, worker displacement, justice, lock-in, and resilience are phrased as conditional mechanisms or research propositions unless directly supported by the reported evidence.

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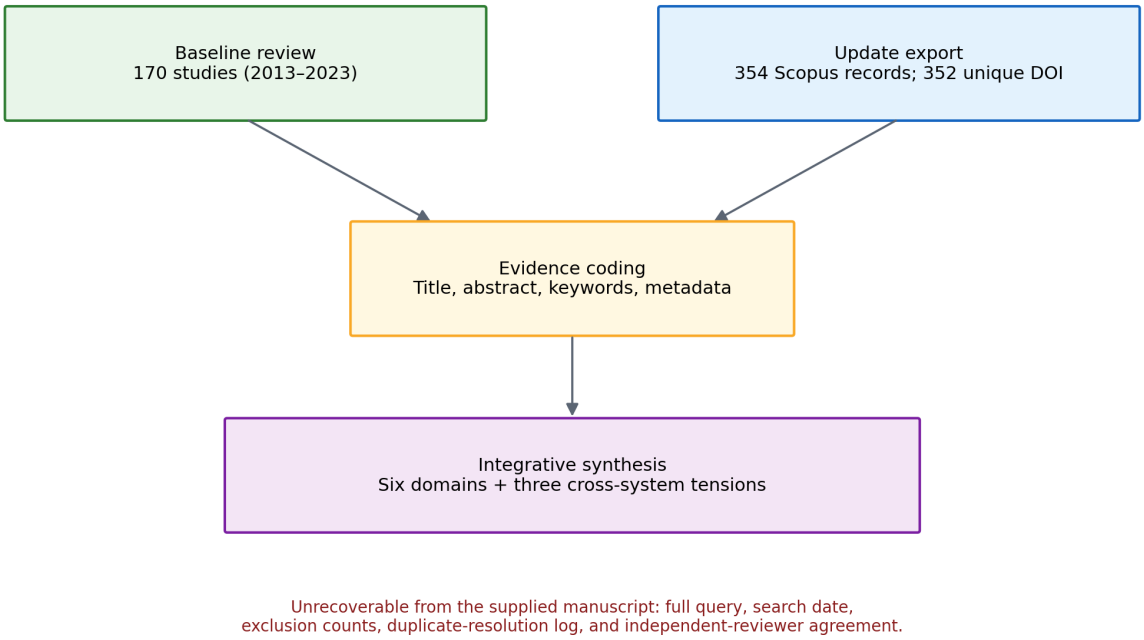


Figure 1. Evidence provenance and documented limits of the update corpus

Note. Counts are reproduced from the supplied manuscript; unavailable screening information is not estimated.

Table 1. Design-sensitive interpretation of the update evidence

Evidence type	Primary contribution	Main inferential limit	Permitted use in this review	Indicative confidence	Ref.
Systematic or critical review	Maps themes and recurring mechanisms	Dependent on prior search and appraisal quality	Corroborating cross-study patterns	Moderate when scope and methods are explicit	Gajera et al. (2026); Devi et al. (2026)
Survey or qualitative case study	Explains behavior, institutions, and lived experience	Context-specific; often cross-sectional	Mechanisms and boundary conditions	Low–moderate; no regional extrapolation	Trushna et al. (2026); Kyambade et al. (2026)
LCA or techno-economic assessment	Compares scenarios and trade-offs	Sensitive to boundaries, inventories, prices, and utilization	Conditional comparisons only	Moderate when sensitivity is reported	Khadka et al. (2026); Marefat et al. (2025)
GIS, optimization, or machine learning	Supports siting, routing, forecasting, or control	Model validity and data representativeness may be uncertain	Decision-support potential, not observed impact	Low–moderate without external validation	Kwikima & Ngole (2025); Dawar et al. (2025)
Laboratory or process study	Establishes technical potential	Scale-up, feedstock variability, emissions, and cost may be unresolved	Process feasibility under stated conditions	Low for municipal-scale outcomes	Aswathy & Ramesh (2026); Xu et al. (2026)
Conceptual or policy analysis	Clarifies institutions, principles, or propositions	Does not estimate causal effects	Framing and hypothesis generation	Propositional	Dharmanu Yudartha & Yuwono (2026); Qiao et al. (2026)

Note. "Author-derived" denotes a transparent analytical aid developed for this review; it is not presented as a validated scale or causal estimate.

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Table 2. Evolution of the MSWM evidence base and interpretive implications

Evidence domain	Earlier emphasis	Recent extension	Persistent limitation	Policy implication	Ref.
System diagnosis	Waste growth, low collection, open dumping, broad barriers	Integrated policy implementation, resilience, circularity, and inequality	Fragmented indicators and weak causal attribution	Diagnose the whole service chain before selecting projects	Zhang et al. (2024); Fong and Omar (2025); Dharmanu Yudartha and Yuwono (2026)
Household interface	Awareness and willingness to sort	Structural constraints, social marketing, identity, incentives, and policy-practice gaps	Self-reported behavior and short follow-up periods	Pair communication with convenient, reliable, and enforceable services	Tahulela et al. (2025a, 2025b); Sierra Puentes et al. (2025); Nguyen (2026)
Spatial operations	Facility siting and route optimization	GIS readiness, dynamic routing, seasonal optimization, and resilience indices	Models often assume clean and complete data	Invest in data governance and operational capacity before automation	Kwikima et al. (2025); Devi and Kalamdhad (2026); Kusi-Appiah and Liu (2026)
Circular recovery	Recycling, composting, anaerobic digestion, and incineration	Integrated biorefineries, advanced thermal routes, material recovery, and market-linked mass balance	Scale-up, contamination, markets, emissions, and financial risk	Use portfolios matched to composition and market demand	Kafle et al. (2025); Gajera and Henrysson (2026); Rao et al. (2026)
Environmental assessment	Local pollution and general climate concern	Scenario LCA, fuzzy LCA, spatial LCA, multi-pollutant modeling, and One Health	Boundary inconsistency and limited local inventories	Compare complete systems and report burden shifting	Choudhary et al. (2025); Maçin (2026); Madhan et al. (2026)
Inclusion and justice	Public participation and informal recycling	Gendered risk, environmental inequality, energy justice, and benefit distribution	Informality is often modeled as leakage rather than labor	Recognize workers and assess distributive effects	Shekari et al. (2025); Kariveliparambil et al. (2026); Kubanza and Mosai (2026)

The distinctive contribution claimed here is an interpretive alignment framework that makes service reliability, material-flow verification, institutional data capability, life-cycle finance, and distributive consequences explicit decision conditions. It does not establish a novel causal theory, empirically tested phase order, or superiority over integrated solid waste management and socio-technical transition approaches.

ANALYTICAL FRAMING: THREE TENSIONS IN CONTEMPORARY MSWM

Three tensions organize the synthesis and prevent the thematic sections from being read as independent technology lists. First, circular and zero-waste aspirations confront uneven service realities: many municipalities must expand safe collection and residual control while building prevention and recovery. Second, data-rich optimization confronts data-poor institutions: digital tools can sharpen decisions, but missing informal flows, inconsistent definitions, weak maintenance, and limited staff capacity can reproduce blind spots. Third, aggregate efficiency confronts distributive justice: lower average cost or emissions can coexist with higher burdens for waste pickers, low-income households, or facility-adjacent communities.

These tensions are used as interpretive questions rather than as predetermined conclusions. For each intervention, the review asks whether service prerequisites exist, whether the data and institutional arrangements can sustain the intervention, and how benefits and risks are distributed. This framing also separates three levels of statement: literature-reported findings, author interpretation across studies, and normative propositions for policy testing.

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The comparison in Table 3 positions the proposed framework relative to established approaches. Its contribution is not the discovery of integration itself—an established principle in ISWM—but a more explicit account of how service reliability, information quality, distributional effects, and implementation capacity condition the performance of circular and digital interventions.

Table 3. Positioning the proposed framework relative to established approaches

Approach	Primary unit of analysis	Established strength	Common blind spot	Role in this review	Ref.
Integrated solid waste management	Linked waste-system functions and stakeholders	Portfolio thinking across collection, recovery, and disposal	May under-specify digital capability and distributive outcomes	Provides the system backbone	Zhang et al. (2024); Ahmed et al. (2026)
Circular economy	Resource retention and value recovery	Moves attention upstream and beyond disposal	Targets may obscure residuals, market dependence, and informal extraction	Defines material-flow ambitions	Gajera et al. (2026); Eamrat et al. (2026)
Socio-technical transition	Interaction of technology, institutions, practices, and learning	Explains why adoption is path-dependent	Can remain abstract at municipal operating level	Supports conditional implementation analysis	Fong et al. (2025); Dharmanu Yudartha & Yuwono (2026)
Institutional and governance approaches	Authority, coordination, finance, rules, and participation	Makes implementation capacity visible	May not follow material and residual flows	Connects formal policy to operational capability	Tahulela & Hashemi (2026); Zuhdi et al. (2026)
Context-conditioned framework (proposed)	Public-service and material-flow chain under local boundary conditions	Links service, data, finance, inclusion, technology, and residual control	Requires empirical testing; not a validated theory	Generates testable propositions and decision questions	Author-derived synthesis

Note. "Author-derived" denotes a transparent analytical aid developed for this review; it is not presented as a validated scale or causal estimate.

FROM A WASTE HIERARCHY TO A SERVICE-AND-MATERIAL-FLOW SYSTEM

The waste hierarchy remains useful, but it is insufficient as an implementation model. Prevention, reuse, recycling, recovery, treatment, and disposal describe preferences among outcomes; they do not specify how institutions make those outcomes occur. Recent reviews increasingly locate performance in the connections between stages. Gajera and Henrysson (2026) frame circular MSWM around resource management, recycling, and recovery, while Rao et al. (2026) explicitly follow technologies from the bin to circularity. Eamrat and Pussayanavin (2026) expose a central accounting problem: informal recovery and market-driven extraction can create gaps between officially recorded waste and actual material flows. These contributions shift attention from isolated treatment efficiencies to system closure.

A service-and-flow perspective begins with the public-service obligation to remove waste safely and predictably. In settings where households cannot rely on collection, messages about segregation compete with rational adaptations such as burning, burying, or informal dumping. Tahulela et al. (2025b) show that disposal behavior is shaped jointly by structural and behavioral constraints; Nguyen (2026) documents discrepancies between household policy and practice in Hanoi; and Trushna et al. (2026) contextualize segregation through multiple stakeholder perspectives in smaller Indian cities. Behavior therefore cannot be reduced to awareness. It is co-produced by storage space, container design, collection schedules, fees, social norms, trust, enforcement, and the perceived destination of separated materials.

This insight changes the interpretation of circular economy policy. Circularity is not achieved when a municipality announces recycling targets or commissions a recovery facility. It requires a chain of compatible actions: households or businesses separate materials; collectors preserve separation; transfer and treatment facilities

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maintain quality; processors meet environmental standards; and markets absorb outputs. A failure at any interface lowers value and shifts residues downstream. The recent evidence on municipal services in Brazil, integrated systems in Pakistan, and circular strategies in East and North Africa illustrates the need to connect administrative performance with material outcomes (Barbosa et al., 2025; Ahmed et al., 2026; Arfasa et al., 2026; Ferehoun et al., 2026).

System boundaries also determine whether an intervention appears successful. A route model can reduce vehicle kilometers while leaving unserved settlements invisible. A compost plant can report high nominal capacity while contaminated input limits product quality. An incinerator can reduce waste volume while increasing fiscal exposure or concentrating emissions and ash hazards. A recycling program can improve municipal statistics while precarious workers bear injury, exposure, and income volatility. The appropriate evaluative unit is therefore the complete chain, including displaced flows and residuals, rather than the facility gate.

The practical implication is sequencing. Foundational collection and controlled disposal remain necessary even within an ambitious circular transition. Prevention and segregation should develop alongside reliable collection; biological and material recovery should scale with feedstock quality and outlets; thermal recovery should follow rigorous composition, emissions, and financial analysis; and engineered landfill capacity should remain available for residues. Integrated solid waste management is valuable precisely because it accepts a portfolio rather than a single preferred technology. Seasonal optimization research further shows that the composition and availability of waste vary through time, so a static design may fail even when its annual averages look adequate (Kusi-Appiah & Liu, 2026).

WASTE PREVENTION AND SOURCE SEGREGATION

Waste prevention is structurally difficult because municipalities usually control downstream services more directly than production, packaging, retail, and consumption. Nevertheless, recent literature strengthens the policy case for moving upstream. Maalouf and Garcia-Tabar (2025) propose a simplified framework for prevention and minimization in developing countries that connects circular economy, Sustainable Development Goals, and environmental, social, and governance principles. De la Cruz et al. (2026) describe the drivers and future directions of the household circular economy, while Tran et al. (2025) examine monitoring of extended producer responsibility compliance and the risk of free riders in Vietnam. Together, these studies suggest that upstream action needs both consumer-facing systems and producer accountability.

Source segregation is the hinge between policy aspiration and recoverable material quality. Mixed waste raises sorting costs, contaminates organics, lowers the value of recyclables, complicates biological processing, and creates avoidable residues. Yet mandatory sorting is credible only when collection preserves the separated streams. Community-based recyclable segregation in Thailand demonstrates how locally embedded programs can connect low-carbon goals, municipal organization, and recyclable collection (Poopuang et al., 2026). Indonesian mixed-methods evidence similarly focuses on improving household sorting, reinforcing the relevance of service design and local context rather than information alone (Sembiring et al., 2024).

Behavioral studies indicate that participation depends on more than environmental concern. Socioeconomic characteristics, place, perceived control, green identity, communication channels, and trust in institutions shape willingness and practice. Community-based social marketing can identify behavioral barriers and tailor interventions, while communication studies show that media channels vary in reach and influence (Sierra Puentes et al., 2025; Ajala et al., 2025). Research on Gen Z and second-hand platforms extends the issue from disposal behavior to reuse and consumption identities (Liu et al., 2026). Mashi et al. (2026) distinguish awareness from practice and emphasize public engagement within circular urban waste systems.

The implementation lesson is to design participation as an operating arrangement. Residents need clear material categories, suitable containers, feasible storage, known collection times, feedback on contamination, and confidence that separated waste remains separated. Variable-rate fees or rewards can reinforce behavior where measurement and equity safeguards are credible, but poorly designed charges may encourage dumping. Enforcement is most defensible after convenient service is available. Policy should also recognize differences among dense settlements, peripheral communities, apartment buildings, markets, institutions, and rural households; a uniform scheme can impose unequal burdens.

Organic waste deserves particular attention because it often dominates the municipal stream in developing regions and controls moisture, odor, vectors, methane formation, and the feasibility of thermal processing. Separating organics can improve composting and anaerobic digestion while increasing the quality of dry recyclables. Biological pathways, however, depend on contamination control, process management, product standards, and demand for compost, digestate, biogas, or other outputs (Syam Babu et al., 2026; Sugumaran et al., 2025). Risk assessment must distinguish the detection of genetic material from actual infectivity when recycled organic products are applied to land, as emphasized by Fikri et al. (2026).

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Prevention and segregation policy should therefore be assessed through linked indicators: per-capita residual generation, participation, capture rate, contamination, missed collection, illegal disposal, worker exposure, processing yield, output quality, and destination. A high participation rate with heavily contaminated material is not equivalent to effective separation. Nor is a reduction in collected waste necessarily prevention; it may reflect service failure or diversion to uncontrolled pathways. Measurement must reconcile household surveys, vehicle and facility records, market transactions, and disposal weights.

COLLECTION, SPATIAL PLANNING, AND DIGITAL DECISION SUPPORT

Collection is often the most visible and expensive municipal function, making it a natural target for optimization. GIS-based analysis can locate collection points, delineate service areas, identify environmentally sensitive zones, and improve vehicle routing. Kwikima et al. (2025) demonstrate GIS-based optimization of collection points and routes in Tanzania, while Devi and Kalamdhad (2026) synthesize the expanding GIS literature. Decision-support systems and hybrid optimization models extend this work toward scheduling and transportation improvement (Mavrin et al., 2026; Karaçizmeli et al., 2026).

The value of optimization depends on what the objective function includes. Minimizing distance or fuel use can improve efficiency, but equitable service requires constraints for coverage, accessibility, road conditions, worker safety, time windows, vehicle capacity, transfer compatibility, and underserved areas. Kasem et al. (2025) connect collection optimization to techno-economic outcomes and the Sustainable Development Goals. Seasonal integrated-system analysis shows why demand, waste composition, and infrastructure performance should not be represented by a single annual average (Kusi-Appiah & Liu, 2026). A resilience-oriented approach must test disruptions, vehicle failure, extreme weather, road access, and demand peaks.

Digital tools now span waste forecasting, automated classification, drone observation, smart bins, IoT monitoring, blockchain traceability, and AI-supported process control. Reviews by Dawar et al. (2025) and Taweesan et al. (2025) describe rapid growth in machine-learning applications. Izquierdo-Horna et al. (2025) forecast generation using household fuel consumption, while Rathod et al. (2026) compare advanced learning models for municipal waste forecasting. Israq et al. (2025) investigate deep-learning segregation, and Bright et al. (2025) review drone, computer-vision, and deep-learning applications. Anitha et al. (2025) propose AI-IoT-graph integration for predictive and resilient systems.

These tools can increase visibility, but they also create new dependencies. Models require stable definitions, representative training data, sensor maintenance, connectivity, skilled staff, procurement support, cybersecurity, and institutional ownership. Tahulela et al. (2025a) report perceived strategic value in GIS while highlighting readiness conditions; Tahulela and Hashemi (2026) show that policy gaps, fragmented governance, capacity limitations, and unreliable services can undermine adoption even when technology is viewed as useful. Digitalization should thus be understood as organizational change supported by technology.

Data quality is also political. Unserved neighborhoods, informal collectors, illegal dumps, and unregistered transactions are precisely the flows most likely to be missing. If algorithms learn only from formal service records, they can optimize existing exclusion. The mass-balance work of Eamrat and Pussayanavin (2026) is consequential because it treats informal extraction as a measurable system component rather than unexplained loss. Blockchain proposals similarly need verified entry points; immutable records do not make inaccurate measurements true (Chakraborty et al., 2026; Ali et al., 2025).

For analytical clarity, this review proposes a four-level digital-capability heuristic: basic records and weighing; spatially enabled planning; real-time operational integration; and predictive or adaptive control. The levels are author-derived from recurring capability requirements in the reviewed abstracts, not an empirically validated maturity scale. Municipalities may progress unevenly across functions, and higher technological complexity is not assumed to be superior when maintenance, interoperability, or accountability are weak.

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Table 4. Decision conditions for digital and analytical tools

Tool family	Primary decision	Essential input	Main value	Principal implementation risk	Ref.
GIS siting and routing	Where to place assets and how to collect	Roads, population, waste points, vehicles, constraints	Coverage, distance, accessibility, spatial transparency	Outdated maps and exclusion of informal settlements	Kwikima et al. (2025); Devi and Kalamdhad (2026)
Forecasting and clustering	How much waste will arise and where	Historical quantities, socioeconomic and seasonal data	Capacity planning and regional differentiation	Biased training data and unstable behavior	Izquierdo-Horna et al. (2025); Taweesan et al. (2025); Rathod et al. (2026)
Computer vision and robotics	How to detect, classify, or sort materials	Labeled images, controlled lighting, representative waste	Faster detection and potentially cleaner fractions	Domain shift, maintenance, and worker displacement	Israq et al. (2025); Bright et al. (2025)
IoT and smart logistics	When bins, vehicles, or facilities require action	Sensors, connectivity, identifiers, maintenance protocols	Real-time visibility and responsive collection	Device failure and fragmented platforms	Anitha et al. (2025); Ali et al. (2025)
Blockchain traceability	Who transferred material and responsibility	Verified measurements and accountable participants	Audit trail for circular supply chains	Immutable but inaccurate inputs and governance complexity	Chakraborty et al. (2026)
AI process control	How to stabilize treatment performance	Calibrated sensors, process history, operator expertise	Prediction, parameter correction, emissions control	Opaque models and weak transferability	Wang et al. (2025); Zhuang et al. (2026)

RECOVERY TECHNOLOGIES AS CONTEXT-DEPENDENT PORTFOLIOS

The recent literature contains substantial technological innovation, but its most important collective message is conditionality. No pathway is universally superior because waste composition, moisture, calorific value, contamination, scale, land, energy prices, markets, climate, regulation, and institutional capacity differ. Technology selection must therefore compare portfolios under local constraints and include preprocessing, residues, emissions, product quality, downtime, and financing. Reviews of global valorization pathways and bin-to-circularity technologies support this portfolio perspective (Kafle et al., 2025; Rao et al., 2026).

Material recycling usually provides high circular value when streams are sufficiently clean and markets exist. Its system performance depends on household separation, collection design, material recovery facilities, price volatility, and the role of informal workers. Eneh et al. (2025) link recycling and resource recovery to public-health challenges in Nigeria. Gajera and Henrysson (2026) synthesize recycling within wider resource management, and Ambrosious and Kandasamy (2025) evaluate barriers to circular practices in municipal plastic waste. Comparative plastic-management research underscores that policy architecture and local capacity affect whether circular ambitions translate into recovered material (Gajera et al., 2026).

Organic waste can be composted, digested, or processed through emerging bioconversion routes. Composting is comparatively accessible, but land, odor, aeration, contamination, and product demand must be managed. Anaerobic digestion can recover energy and nutrients, yet feedstock preparation, process stability, gas use, digestate quality, and capital operation are decisive. Marefat et al. (2025) examine financial feasibility and optimization globally, while Nsekela et al. (2026) review optimization of biogas production from municipal waste in sub-Saharan Africa. Elgarahy et al. (2025) connect biowaste valorization with AI-supported optimization, illustrating the convergence of biological and digital innovation.

Thermal options include incineration, gasification, pyrolysis, and related conversion processes. Their potential advantages include volume reduction, energy recovery, and treatment of selected residuals; constraints include moisture, heterogeneous feedstock, emissions control, ash management, capital intensity, technical skill, and long-

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term feedstock commitments. Panwar et al. (2025) assess plasma gasification through life-cycle thinking; Aswathy et al. (2026) review municipal waste pyrolysis; and Abedin et al. (2025) synthesize advances in energy recovery. Waste-to-hydrogen and integrated biorefinery studies expand the product set, but emerging pathways require particular caution when evidence remains laboratory- or model-based (Aji Nugroho et al., 2026; Van Tan et al., 2026).

Incineration illustrates the need to link plant performance to system governance. Advanced modeling can improve multi-pollutant prediction and correct process parameters (Wang et al., 2025; Zhuang et al., 2026). Full-scale work on co-incineration examines process intensification and emissions reduction (Xu et al., 2026). Yet modeling does not replace continuous monitoring, competent operation, transparent disclosure, ash controls, and enforceable limits. Health evidence around airborne emissions demands careful exposure assessment, while fly ash recovery must manage toxic risks before construction use can be considered sustainable (Di Maria et al., 2024; Joseph et al., 2026).

Energy recovery also raises justice questions. Long-term contracts may prioritize plant utilization over prevention and recycling. Tariffs and public guarantees can shift technology risk to municipalities and residents. Facility siting can concentrate environmental burdens. Shekari et al. (2025) therefore integrate energy-justice principles into multi-criteria decisions. The relevant question is not simply whether waste can produce energy, but who benefits, who pays, what alternatives are displaced, and whether the system remains adaptable as waste prevention succeeds.

Industrial residues and construction materials represent another circular frontier. Innovations use ash, sludge, gangue, biomass residues, or waste-derived components in construction and other products. Such pathways can reduce virgin-material demand and disposal, but require leaching, durability, exposure, and life-cycle testing. Keskin et al. (2024) review industrial solid residual waste applications, while Joseph et al. (2026) focus on health risks and treatment of municipal incinerator fly ash. Circular claims should be based on safe substitution and avoided burdens, not merely the presence of waste in a new product.

Table 5. Technology portfolio appraisal for developing-region municipalities

Pathway	Suitable feedstock and enabling conditions	Potential contribution	Critical safeguards	Common failure mode	Ref.
Material recovery	Clean paper, metals, glass, and selected plastics; stable buyers	Avoided disposal and secondary materials	Source segregation, worker protection, quality standards, market agreements	Contamination and price volatility	Gajera and Henrysson (2026); Ambrosious and Kandasamy (2025)
Composting	Source-separated organics; land and product demand	Soil amendment and methane avoidance	Contamination limits, odor and vector control, product testing	Unsold or contaminated compost	Syam Babu et al. (2026); Khare et al. (2025)
Anaerobic digestion	Consistent wet organics; energy and digestate outlets	Biogas, energy, nutrient recovery	Pretreatment, process monitoring, digestate standards	Unstable feedstock and high operating burden	Marefat et al. (2025); Nsekela et al. (2026)
Biodrying and mechanical-biological treatment	Mixed residuals where separation is developing	Moisture reduction and fuel preparation	Mass balance, odor control, market for outputs	Producing low-quality fuel and residuals	Sayın et al. (2025)
Incineration with energy recovery	Sufficient dry combustible residuals and reliable scale	Volume reduction and power or heat	Continuous emissions control, ash management, fiscal stress tests	Feedstock lock-in and pollution-control failure	Wang et al. (2025); Xu et al. (2026); Di Maria et al. (2024)

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Pathway	Suitable feedstock and enabling conditions	Potential contribution	Critical safeguards	Common failure mode	Ref.
Pyrolysis and gasification	Prepared, relatively controlled feedstock	Fuels, syngas, char, and energy	Preprocessing, product standards, lifecycle and market validation	Extrapolation from pilot evidence	Panwar et al. (2025); Aswathy et al. (2026)
Engineered landfill and gas recovery	Unavoidable residuals; appropriate geology and operation	Safe containment and possible methane use	Liners, leachate, gas, cover, monitoring, closure funding	Nominal landfill operation without engineered controls	Shumba et al. (2026); Rajput and Li (2027)

LANDFILLS, POLLUTION, HEALTH, AND CLIMATE

Even high-performing circular systems generate residuals. The transition away from open dumping therefore requires engineered disposal rather than the rhetorical elimination of landfills. The baseline review documented the environmental and health consequences of uncontrolled disposal, including air, soil, and water pollution, flooding, vector-borne disease, and greenhouse-gas emissions (Zhang et al., 2024). Recent studies add more spatially and biologically specific evidence on leachate, microplastics, air quality, community experience, and One Health.

Leachate illustrates the long time horizon of residual management. Its composition varies with waste age, climate, landfill operation, and hydrology. Shumba et al. (2026) identify treatment gaps and opportunities in Southern Africa. Tashakori Hashemi et al. (2026) examine impacts on river quality in Iran, while Haligamo et al. (2026) assess surface-water pollution near an Addis Ababa dumping site. Kooch et al. (2025) show that soil-health indicators can be affected differently under contrasting climate conditions. These studies argue for site-specific monitoring rather than generic assumptions about attenuation.

Open dumps also produce mixed exposures through smoke, dust, odors, contaminated water, vectors, unstable slopes, and direct contact. Edet et al. (2026) characterize carbon-footprint and air-quality signatures around a Nigerian dumpsite, and Kyambade et al. (2026) center community experience and environmental-health risk near Uganda's Kiteezi landfill. Gebrekidan et al. (2024) interpret improper MSWM through a One Health lens in Ethiopia. The convergence of environmental sampling and lived experience is important because facility averages can obscure exposure peaks, livelihood dependence, and vulnerability.

Climate policy creates both opportunities and accounting challenges. Landfill methane avoidance, material substitution, recycling, composting, digestion, and energy recovery can reduce emissions under appropriate conditions. Scenario LCA in Türkiye evaluates decarbonization pathways toward recovery targets, while work in Kathmandu and Lisbon compares system-level environmental impacts (Maçin, 2026; Khadka et al., 2026; Costa et al., 2026). The direction and scale of benefits depend on counterfactual energy systems, collection emissions, material substitution, methane capture, contamination, and treatment performance.

Life-cycle assessment should therefore inform rather than mechanically determine decisions. Results depend on functional units, system boundaries, allocation rules, time horizons, local inventories, and avoided-product assumptions. Choudhary et al. (2025) integrate fuzzy logic to address uncertainty, and Madhan et al. (2026) combine experimental, GIS, and life-cycle components for spatial sustainability assessment. Khadka et al. (2026) and Costa et al. (2026) show that comparative outcomes change with local inventories, scenarios, and system boundaries.

Climate resilience must complement mitigation. Floods can mobilize dumped waste and leachate; heat can intensify odor and biological activity; storms disrupt collection; and rainfall changes waste moisture and treatment performance. City-level sustainability and resilience indices, such as the Bangkok application by Swan et al. (2026), can support multi-dimensional monitoring. However, composite indices should retain interpretable sub-indicators so that apparent progress in one dimension does not mask deterioration in another.

GOVERNANCE, FINANCE, AND INSTITUTIONAL CAPACITY

The decisive bottleneck in many systems is not knowledge of treatment options but the capacity to coordinate and sustain them. Policy implementation reviews describe fragmented mandates, inconsistent enforcement, resource limitations, and weak alignment between formal policy and local conditions (Dharmanu Yudartha & Yuwono, 2026). Evidence from Pakistan connects stakeholder engagement with integrated sustainability dimensions (Khan et al., 2026), while feasibility analysis of integrated MSWM emphasizes the institutional context of the Global South (Ahmed et al., 2026). These studies support governance as an operating capability rather than a collection of policy documents.

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Clear allocation of responsibility matters across municipal departments, private contractors, producer-responsibility organizations, communities, and informal enterprises. When responsibility is diffuse, data are incomplete, contracts reward tonnage rather than outcomes, and enforcement becomes selective. Collaborative governance research on urban waste banks shows the importance of stakeholder participation and structural relationships (Zuhdi et al., 2026). Intergovernmental cooperation research on zero-waste cities similarly demonstrates that incentives and strategic interaction shape implementation (Qiao et al., 2026).

Finance is the connective tissue of the system. Collection requires recurrent expenditure; transfer and treatment facilities require capital and competent operation; landfills require monitoring and closure funds; social inclusion requires transition support; and data systems require maintenance. Yet financial analysis is comparatively sparse in the supplied corpus. Work on small-municipality innovation, service efficiency in Brazil, grassroots financing in Tanzania, and anaerobic-digestion feasibility indicates a shift toward institutional economics, but the field still privileges technology costs over whole-system fiscal sustainability (Paes et al., 2025; Barbosa et al., 2025; Ilomo & Charles, 2025; Marefat et al., 2025).

A robust financing framework distinguishes affordability, cost recovery, value recovery, and fiscal risk. User charges may support recurrent costs but must account for ability to pay and service quality. Producer responsibility can shift costs upstream, but requires monitoring to prevent free riding (Tran et al., 2025). Revenues from recyclables, compost, energy, or carbon benefits can contribute, but volatile markets should not be treated as guaranteed base funding. Public-private partnerships can mobilize capacity, yet contracts require transparent performance indicators, risk allocation, adjustment mechanisms, and public oversight.

Procurement is a hidden determinant of performance. Municipalities often purchase vehicles, software, or treatment capacity without lifecycle maintenance plans, interoperability requirements, spare parts, or workforce development. Technology vendors may optimize against specifications that ignore informal flows or changing waste composition. A capacity-first procurement process begins with service objectives, credible data, alternatives analysis, and total cost of ownership. It includes training, maintenance, data access, emissions obligations, residue responsibility, and exit provisions.

Institutional learning requires feedback. Waste plans should connect targets to annual budgets, operational dashboards, contract management, facility monitoring, and public reporting. Targets should be expressed through measurable outcomes—coverage, reliability, capture, contamination, recovery yield, controlled disposal, emissions, injuries, affordability, and complaints—not solely through installed capacity. This creates a pathway from policy to implementation and allows course correction when assumptions fail.

INFORMALITY, PARTICIPATION, AND ENVIRONMENTAL JUSTICE

Informal workers frequently provide collection, sorting, trading, and recovery services that formal statistics undervalue. Their activities can raise recycling rates and support livelihoods, yet workers may face hazardous exposure, unstable income, stigma, harassment, and exclusion from policy decisions. Treating the sector solely as a data problem or inefficiency misses its institutional and distributive significance. Eamrat and Pussayanavin (2026) show how informal recycling affects mass-balance accounting, while Kariveliparambil et al. (2026) emphasize gendered health vulnerability among women waste pickers.

Inclusion should not mean absorbing workers into systems on terms that destroy livelihoods. It can involve legal recognition, occupational health protection, access to sorting infrastructure, cooperatives, service contracts, price transparency, social protection, childcare, training, and representation in planning. The appropriate mix varies with local organization and markets. Transition assessments should identify who loses access to valuable materials when facilities or exclusive contracts are introduced and should budget for mitigation.

Environmental injustice is also spatial. Kubanza and Koenaite (2026) connect urban planning failures and waste-related harm in Alexandra, Johannesburg. Poor communities may receive less reliable collection while living closer to dumps, transfer stations, polluted waterways, or transport routes. Facility siting processes that rely only on technical exclusion criteria can reproduce this pattern. Spatial suitability analysis should therefore include cumulative exposure, service deficits, tenure insecurity, livelihood dependence, and procedural participation.

Public participation is most effective when it changes decisions and service design. Consultation after a technology or site has been selected does little to build legitimacy. Community-based intervention research in Colombia links willingness, barriers, and spatial strategies, while community segregation in Thailand demonstrates an operational partnership rather than a one-time awareness campaign (Aristizábal Cuellar et al., 2025; Poopuang et al., 2026). Participation should span problem definition, option assessment, implementation, monitoring, and grievance resolution.

Justice should be incorporated into routine evaluation. Distributional indicators can track service coverage by neighborhood, household burden relative to income, worker earnings and injuries, proximity to facilities, odor and air-quality complaints, and access to recovered value. Procedural indicators can assess information access, representation, consent processes, complaint response, and transparency. Recognition indicators can test whether

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policies acknowledge informal workers, renters, migrants, women, and peripheral settlements. These measures make visible trade-offs that aggregate efficiency metrics conceal.

The five phases in Table 6 are author-developed heuristic decision prompts, not empirically estimated thresholds or a universally valid chronological sequence. Their decision gates should be interpreted as questions for local evaluation, not binding recommendations supported by comparative effect estimates.

INTEGRATED ASSESSMENT AND CAUTIOUS POLICY SEQUENCING

The evidence supports an integrated assessment framework with six interacting capabilities: service foundations, material-flow integrity, governance, finance, inclusion, and intelligence. Service foundations include reliable collection and controlled residual disposal. Material-flow integrity covers prevention, separation, preservation of clean streams, processing yield, markets, and mass-balance closure. Governance includes clear mandates, enforcement, contracts, and learning. Finance covers recurrent affordability and lifecycle risk. Inclusion concerns participation, labor, and justice. Intelligence includes data standards, GIS, forecasting, LCA, and decision support.

These capabilities are complements. Digital intelligence cannot compensate for unreliable service; treatment capacity cannot compensate for contaminated feedstock; formal targets cannot compensate for missing finance; and high recovery cannot compensate for unsafe labor or uncontrolled residues. The framework therefore rejects linear modernization narratives in which cities progress by adopting increasingly sophisticated technology. Progress is better understood as alignment: a municipality becomes capable of more complex interventions as its upstream and downstream conditions mature.

Table 6. Context-conditioned implementation sequence and monitoring logic (author-derived propositions for empirical testing)

Phase	Priority actions	Readiness test	Core indicators	Decision gate	Ref.
1 Stabilize	Map generators and flows; extend reliable collection; eliminate routine open burning; establish controlled disposal	Basic asset, route, cost, and disposal records are complete enough for management	Coverage, missed collection, illegal dumps, controlled disposal, worker incidents	Do not scale complex treatment while substantial waste remains uncollected	Zhang et al. (2024); Martínez Ángeles et al. (2026)
2 Separate	Introduce simple source categories; align containers and schedules; protect separated streams; engage communities	Participation produces material of usable quality	Participation, capture, contamination, complaint resolution	Expand only where collection reliability and downstream outlets are proven	Nguyen (2026); Trushna et al. (2026); Poopuang et al. (2026)
3 Recover	Develop material and organic recovery portfolios; integrate informal workers; secure product standards and buyers	Mass balances close and outputs meet market and safety requirements	Recovery yield, residue rate, output quality, worker income and safety	Reject nominal capacity without verified feedstock and markets	Eamrat and Pussayanavin (2026); Gajera and Henrysson (2026)
4 Optimize	Apply GIS, forecasting, route optimization, LCA, and performance contracts	Data are sufficiently complete, timely, and institutionally owned	Cost per served household, route performance, emissions, data completeness	Automate only decisions with accountable human oversight	Tahulela and Hashemi (2026); Devi and Kalamdhad (2026)

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Phase	Priority actions	Readiness test	Core indicators	Decision gate	Ref.
5 Decarbonize and adapt	Compare full-system scenarios; capture methane; improve efficiency; stress-test climate and fiscal risks	Environmental gains remain robust under uncertainty and disruption	Lifecycle GHG, methane capture, downtime, fiscal exposure, resilience	Select pathways that avoid burden shifting and technology lock-in	Maçin (2026); Swan et al. (2026)

In Phase 1, authorities establish a reliable service floor. This is not an argument for postponing circularity indefinitely; it is recognition that uncollected waste undermines every downstream objective. Mapping should include formal and informal flows, uncontrolled sites, service disparities, sensitive receptors, and institutional responsibilities. Immediate risk reduction can proceed through closing dangerous dumps, improving collection, introducing worker protection, and creating controlled residual capacity.

Phase 2 institutionalizes source segregation with a limited number of understandable categories. Programs should start where collection reliability and processing outlets exist, then expand through monitored learning. Communication should explain not only how to sort but why, when, and where materials go. Feedback on contamination and service failure allows mutual accountability. Enforcement should focus first on large generators and organizations capable of compliance, while households receive accessible services and graduated support.

Phase 3 builds recovery portfolios. Material-recovery and organic-treatment capacity should be modular where uncertainty is high. Contracts should reward usable output and verified diversion rather than incoming tonnage alone. Informal workers should participate in design and gain safe, compensated roles. Markets should be assessed through quality specifications, demand, logistics, and price risk. Residues must be quantified and safely disposed.

Phase 4 uses data and analytical tools to improve a functioning system. GIS can identify spatial service gaps, optimization can reduce cost and emissions, and forecasting can improve capacity planning. LCA and multi-criteria analysis can compare portfolios. Digital platforms should use interoperable standards and preserve public access to essential operational data. Algorithms should be audited for geographic and socioeconomic bias.

Phase 5 deepens decarbonization and resilience. Scenario assessment should include prevention success, energy-system change, carbon uncertainty, climate hazards, technology downtime, and fiscal stress. The system should remain adaptable rather than locked into a single high-throughput facility. Engineered landfill, leachate control, and long-term monitoring remain necessary for residues even when diversion rises.

REGIONAL DIFFERENTIATION AND TRANSFERABILITY

The label “developing regions” is analytically useful only when it does not erase variation. The baseline comparison of Asia and Africa identified shared pressures—urbanization, resource constraints, informal disposal, weak enforcement, and unequal capacity—but also wide variation within and between continents (Zhang et al., 2024). The update corpus extends this geography across South and Southeast Asia, East and Southern Africa, Latin America, the Middle East, and transitional economies. Its comparative value lies less in ranking regions than in identifying combinations of conditions that shape feasible policy sequences.

In rapidly growing metropolitan areas, waste volumes can justify transfer infrastructure and larger treatment assets, but density, congestion, land scarcity, and administrative fragmentation complicate collection and siting. Data may exist across multiple agencies without compatible definitions. Metropolitan reforms therefore require inter-jurisdictional governance, coordinated tariffs, shared facilities, and mechanisms to prevent richer districts from exporting residual burdens. Work on Bangkok’s resilience index, Hanoi’s policy-practice gap, and urban inequality in Johannesburg illustrates different dimensions of this coordination problem (Swan et al., 2026; Nguyen, 2026; Kubanza & Koenaite, 2026).

Smaller cities and rural municipalities face a different scale problem. Low density and longer travel distances increase collection costs, while limited technical staff and small waste quantities can make capital-intensive plants uneconomic. At the same time, smaller administrations may have closer community relationships and opportunities for modular organics and material recovery. Evidence on innovation in small municipalities and GIS readiness in rural South Africa suggests that institutional capability and intermunicipal collaboration may matter more than purchasing sophisticated standalone systems (Paes et al., 2025; Tahulela & Hashemi, 2026).

South Asian evidence emphasizes high organic fractions, dense settlement, informal recovery, seasonal variation, and intense pressure on disposal sites. Integrated feasibility studies in Pakistan, household segregation work in India, and LCA in Kathmandu show why system design must combine reliable collection, organics

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management, recognition of informal markets, and controlled residual disposal (Ahmed et al., 2026; Trushna et al., 2026; Khadka et al., 2026). Advanced thermal options may have a role for appropriate residual streams, but high moisture and mixed collection can undermine nominal energy performance.

Southeast Asian research increasingly connects community programs, extended producer responsibility, digital systems, and low-carbon goals. The Thai community-segregation case illustrates locally organized recyclable recovery; Vietnamese research highlights both producer-compliance monitoring and household policy-practice discrepancies (Poopuang et al., 2026; Tran et al., 2025; Nguyen, 2026). These cases show that national policy instruments and neighborhood practices are mutually dependent: producer schemes need traceable collection, while household schemes need markets and institutional follow-through.

African studies in the update corpus foreground service inequality, informal livelihoods, institutional capacity, dumpsite exposure, and circular opportunity. East African zero-waste reviews and corridor-scale circular analysis propose recovery pathways, but empirical studies show persistent barriers in collection, public engagement, financing, and pollution control (Arfasa et al., 2026; Lasaki et al., 2026; Ilomo & Charles, 2025). Research from Ethiopia, Nigeria, Uganda, Tanzania, and South Africa reinforces the need to treat environmental health and distributive justice as core system objectives (Gebrekidan et al., 2024; Edet et al., 2026; Kyambade et al., 2026; Kwikima et al., 2025; Kubanza & Koenaite, 2026).

Latin American evidence contributes strong examples of behavioral intervention, municipal efficiency, renewable-energy assessment, and national policy stress testing. Community-based social marketing in Colombia focuses on behavioral mechanisms, Brazilian studies analyze service productivity and energy potential, and an agent-based Costa Rican study examines equitable transitions (Sierra Puentes et al., 2025; Barbosa et al., 2025). These contributions encourage closer integration between behavioral evidence, public-sector performance, and scenario analysis.

The regional comparison yields four propositions. First, scale determines feasible logistics and technology, but institutional cooperation can partly overcome scale constraints. Second, composition—especially organic content and moisture—should be measured locally and seasonally before treatment selection. Third, informal recovery is a system component across many contexts, although its organization and bargaining power vary. Fourth, transition speed should be constrained by demonstrated service, market, regulatory, and financial readiness rather than by international technology fashions.

A decision architecture for municipalities

A municipality can translate these propositions into a structured alternatives assessment. The first step is a baseline that reconciles generation estimates, collection records, informal extraction, processing, illegal disposal, and landfill receipts. The baseline should describe uncertainty and seasonal change. Where scales are absent, short-duration weighing campaigns and composition audits can establish decision-grade estimates. Where informal transactions are important, participatory mapping and market surveys should complement official records (Eamrat & Pussayanavin, 2026; Gebrekidan et al., 2024).

The second step is problem decomposition. Authorities should separate failures of coverage, reliability, segregation, transport, treatment, disposal, finance, enforcement, and market development. A city with low collection coverage has a different priority from one with reliable collection but declining landfill capacity. Problem decomposition prevents a flagship facility from becoming the answer to several unrelated failures. Reviews of disposal practices and integrated systems support this diagnostic orientation (Martínez Ángeles et al., 2026; Fong & Omar, 2025).

The third step is option design as portfolios. Each portfolio should specify prevention instruments, collection configuration, source categories, transfer arrangements, treatment capacity, markets, residual disposal, staffing, data, and regulation. At least one incremental option should be compared with high-capital alternatives. Portfolio design should account for modularity and reversibility because population, markets, and policy can change. Circular and biological reviews demonstrate the expanding option set, but also the need to combine processes rather than treat them as substitutes in all circumstances (Kafle et al., 2025; Syam Babu et al., 2026; Gajera & Henrysson, 2026).

The fourth step is multi-dimensional appraisal. Financial analysis should include capital, operation, maintenance, replacement, closure, debt, foreign exchange, and revenue uncertainty. Environmental analysis should include climate, air, water, soil, resource substitution, and residuals. Social analysis should include affordability, access, employment, occupational safety, siting, and participation. Institutional analysis should test staffing, procurement, contracting, monitoring, and enforcement. Multi-criteria methods can structure trade-offs, but weights and assumptions should be disclosed and stress-tested (Sayın et al., 2025; Shekari et al., 2025).

The fifth step is staged implementation with learning thresholds. Pilots should test the uncertain mechanism rather than simply demonstrate a small version of a favored project. A segregation pilot should test capture, contamination, route integration, processing, markets, and user burden. A digital pilot should test data quality, staff

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use, maintenance, and decision improvement. A treatment pilot should test realistic feedstock, downtime, emissions, residues, and products. Scale-up should occur only when predefined thresholds are met.

The sixth step is transparent performance management. Public dashboards should report a limited set of intelligible measures and disclose data limitations. Contracts and budgets should align with those measures. Independent audits can verify weights, emissions, worker conditions, and destination claims. Complaint data should be analyzed spatially to identify service inequality. This feedback architecture turns policy into an adaptive process rather than a static plan.

Indicators that connect activities to public value

Input indicators—vehicles, bins, staff, facility capacity, or software licenses—are easy to report but weak measures of success. Process indicators improve accountability by tracking route completion, weighing coverage, segregation participation, contamination, downtime, and monitoring compliance. Output indicators record collected tonnes, recovered products, energy, compost, rejects, and controlled disposal. Outcome indicators address public value: reduced exposure, lower lifecycle emissions, affordable service, safer work, less dumping, and resilient operations.

Indicator design should prevent perverse incentives. Paying contractors only per tonne collected can discourage prevention. Rewarding nominal diversion can promote low-quality outputs that later return to disposal. Measuring route efficiency without coverage can disadvantage remote settlements. Reporting energy generation without net lifecycle effects can hide auxiliary fuel or displaced recycling. Balanced indicators should therefore combine service, material, environmental, financial, and justice dimensions.

Material indicators should include per-capita generation, collection coverage, capture by material, contamination, processing yield, product sales, rejects, and reconciled residuals. Environmental indicators should include lifecycle greenhouse gases, methane capture, criteria pollutants, leachate quality, water and soil conditions, odor, and fire events. Financial indicators should include total cost per household served, cost per tonne by function, revenue reliability, arrears, subsidy incidence, maintenance backlog, and contingent liabilities.

Social and institutional indicators are equally necessary. Service reliability should be disaggregated by neighborhood and settlement type. Affordability can be expressed as household expenditure relative to income. Worker measures should cover formal and informal employment, earnings stability, protective equipment, injury, exposure, and access to social protection. Governance measures should include budget execution, contract compliance, enforcement consistency, complaint resolution, data completeness, and public disclosure. The resilience literature suggests adding redundancy, recovery time after disruption, and capacity to operate under seasonal extremes (Swan et al., 2026; Kusi-Appiah & Liu, 2026).

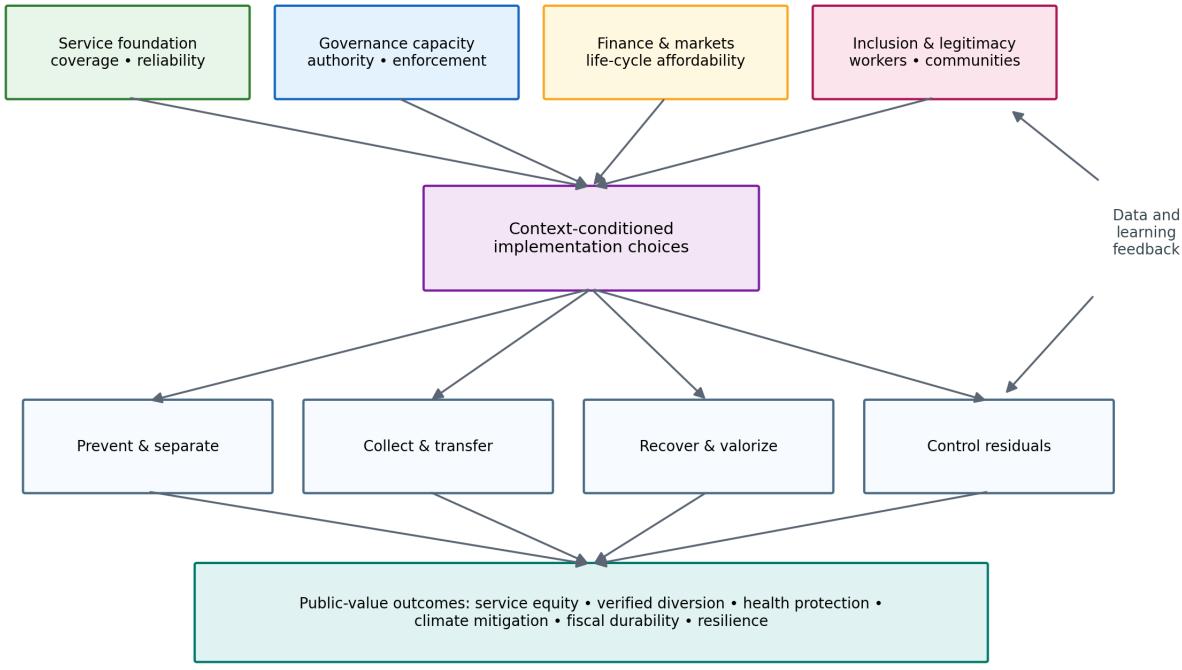


Figure 2. Context-conditioned MSWM framework and feedback structure

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Note. The relationships are propositions generated from the synthesis and require empirical validation.

Propositional framework and testable relationships

Figure 2 presents an author-developed conceptual framework, not a validated theory. It proposes that service reliability, governance capacity, life-cycle finance and markets, inclusion and legitimacy, and data capability jointly condition implementation choices. Four propositions follow: reliable collection should strengthen the effect of segregation on recoverable quality; data systems should improve outcomes only when definitions, maintenance, and decision authority are aligned; recovery technologies should perform better when feedstock and offtake conditions are stable; and efficiency gains should be evaluated together with exposure, affordability, and livelihood effects. These propositions require longitudinal and comparative testing.

A context-conditioned propositional framework can connect these perspectives. It treats outcomes as the product of five relationships: alignment between rules and operational authority; alignment between household practices and service design; alignment between feedstock and technology; alignment between outputs and markets; and alignment between costs, benefits, and political legitimacy. Misalignment at one interface can propagate through the system. For example, unreliable collection lowers trust and segregation, contaminated material lowers recovery yield, weak markets lower revenue, fiscal stress reduces maintenance, and deteriorating service further lowers trust.

This feedback structure explains persistence and transition. Vicious cycles arise when poor service, low payment, weak revenue, deferred maintenance, and dumping reinforce one another. Virtuous cycles can arise when reliable service builds trust, separation improves product quality, recovery reduces residuals, transparent performance supports willingness to pay, and stable finance sustains operations. Digital tools can accelerate either cycle: they can expose gaps and improve coordination, or they can legitimize biased records and divert resources from service fundamentals.

The theory therefore predicts that isolated interventions will show heterogeneous and often temporary effects. Bundled interventions should perform better when they target linked constraints, but excessive complexity can overwhelm institutions. A plausible reform package may be the smallest coherent set of changes capable of closing a feedback loop. This proposition is testable through comparative longitudinal research that measures institutional change, behavior, material flows, finance, and environmental outcomes together.

Implications for evidence translation and scale up

Evidence translation requires a disciplined distinction among efficacy, effectiveness, scalability, and sustainability. Laboratory research can establish conversion potential; pilots can reveal operating constraints; city-scale evaluations can show effects on service and material flows; and longitudinal studies can reveal whether institutions and finance sustain performance. These stages answer different questions. Treating a high experimental yield as proof of municipal feasibility collapses the chain and conceals preprocessing, contamination, downtime, residue management, market absorption, and operator capability. The same caution applies to predictive accuracy in digital studies: a model can perform well on historical data without improving an operational decision.

Scale-up should be treated as redesign rather than multiplication. Larger catchments alter transport distances, feedstock heterogeneity, stakeholder numbers, contract exposure, and the consequences of failure. Centralized plants can gain economies of scale but increase dependence on transfer infrastructure and stable throughput. Decentralized systems can reduce hauling and support local participation but demand distributed quality control and multiple competent operators. Comparative portfolios should test hybrid networks in which neighborhood or district-scale separation and organics treatment connect to regional facilities for specialized residuals.

Replication also requires reporting negative and null results. The literature is vulnerable to publication bias toward successful pilots, high model accuracy, and favorable scenario outcomes. Studies should report equipment downtime, rejected loads, contamination, community opposition, delayed procurement, output-price weakness, and enforcement failure. These observations reveal boundary conditions and can prevent repeated investment mistakes. Review articles should differentiate demonstrated practice from proposed frameworks and should not count multiple publications from one project as independent confirmation.

Knowledge co-production can improve external validity. Municipal operators understand route constraints and maintenance realities; informal workers understand recoverable-material markets; residents understand storage and access barriers; regulators understand compliance capacity; and researchers contribute measurement and comparison. Involving these groups early can improve problem definition, identify unintended effects, and produce indicators that remain usable after a study ends. Co-production does not remove conflict, but it makes trade-offs explicit and improves the legitimacy of implementation choices.

Finally, evidence translation should retain reversibility. Under deep uncertainty, modular infrastructure, adaptable contracts, open data standards, and staged investment allow learning without committing the municipality to a single forecast. Reversibility is especially important where waste prevention, producer responsibility, energy

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prices, or climate conditions may change feedstock quantity and value. A robust strategy performs acceptably across plausible futures; it is not merely optimal under one modeled scenario.

The resulting approach also clarifies the role of national and international support. Grants and technical assistance should strengthen durable municipal functions—asset management, measurement, procurement, contract oversight, environmental monitoring, and workforce development—alongside physical infrastructure. Funding conditions can require open performance data and inclusive transition plans without imposing one technology. Regional platforms can pool laboratories, specialized treatment, training, and market development where individual municipalities lack scale. Donors and development banks should compare avoided harm, service equity, and fiscal resilience across the full portfolio, and should disclose assumptions about tariffs, feedstock, energy sales, and carbon value. This orientation turns external support from project delivery into capability formation and reduces the risk that facilities become stranded when warranties, consultants, or concessional finance end.

RESEARCH AGENDA

Close the material mass balance

Many studies report collection, recycling, or treatment rates independently, making it impossible to reconcile generation with destinations. Future research should establish common mass-balance protocols across household separation, formal collection, informal extraction, transfer, processing, product sales, rejects, and disposal. Uncertainty intervals should be reported rather than hidden. The work of Eamrat and Pussayanavin (2026) provides a strong direction by explicitly quantifying informal and market-driven flows.

Move from intentions to observed behavior

Cross-sectional surveys remain common, but intentions do not necessarily predict sustained sorting, payment, reuse, or participation. Longitudinal, quasi-experimental, and field-experimental designs should evaluate service changes, pricing, feedback, communication, and enforcement. Studies should measure contamination and capture through waste audits, not only self-reports. Behavioral heterogeneity by housing, gender, income, tenure, and neighborhood should be incorporated (Mashi et al., 2026; Tufa et al., 2026; Rufai et al., 2026).

Connect modeled optimization to operational performance

Routing, forecasting, machine learning, and process models often demonstrate technical accuracy without evaluating procurement, staff adoption, maintenance, or real-world service effects. Future studies should report data provenance, missingness, model drift, transferability, implementation costs, human oversight, and post-deployment outcomes. Comparisons with simple baselines are essential. GIS readiness and institutional barriers should be treated as explanatory variables, not footnotes (Tahulela et al., 2025; Tahulela & Hashemi, 2026).

Standardize system boundaries in environmental assessment

LCA results are difficult to compare when functional units, avoided products, methane assumptions, informal recycling, collection coverage, and residual treatment differ. Research should publish transparent inventories, sensitivity analyses, and distributional extensions. Spatial LCA can connect aggregate impacts to exposed communities, while fuzzy or probabilistic methods can represent uncertainty (Choudhary et al., 2025; Madhan et al., 2026; Costa et al., 2026).

Evaluate fiscal sustainability and lock in

The literature needs more long-term evidence on operating expenditure, tariff affordability, municipal credit risk, contractual guarantees, downtime, spare parts, foreign-exchange exposure, output-price volatility, and closure liabilities. Techno-economic studies should include institutional capacity and realistic utilization rather than ideal plant performance. Scenario analysis should test the financial effects of successful prevention, which may reduce feedstock for high-throughput facilities (Kasem et al., 2025; Marefat et al., 2025).

Make justice measurable

Justice is increasingly recognized but inconsistently operationalized. Studies should measure changes in exposure, service access, household expenditure, worker income, occupational health, decision influence, and proximity to hazards. Gender-disaggregated and neighborhood-level data are needed. Energy and circularity assessments should report who receives benefits and who bears residual risk (Shekari et al., 2025; Kariveliparambil et al., 2026; Kubanza & Koenaite, 2026).

Study institutional change over time

Policies are frequently evaluated as texts or at a single moment. Longitudinal institutional research should trace budgets, staff capability, enforcement, contracts, data use, intergovernmental relations, and stakeholder coalitions. Comparative city research can distinguish transferable mechanisms from context-specific arrangements. Policy

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implementation should be linked to material and health outcomes rather than assessed through adoption alone (Chauhan et al., 2025; Dharmanu Yudartha & Yuwono, 2026; Qiao et al., 2026).

Build climate-resilient waste systems

Waste infrastructure is exposed to rainfall, flooding, heat, fire, landslides, and service disruption. Research should integrate climate projections with siting, route accessibility, leachate generation, biological performance, fire risk, and emergency debris. Seasonal and disruption scenarios should inform redundancy and contingency planning (Kusi-Appiah & Liu, 2026; Swan et al., 2026; Shumba et al., 2026).

No study-by-study evidence-to-claim audit or formal methodological risk-of-bias ratings can be reconstructed from the reported abstract-level materials. The confidence descriptions in Table 1 are design-level interpretive cautions only. The corpus does not establish prevalence of findings across studies, effect sizes, comparative intervention impacts, or consistent regional subgroup estimates. These missing elements restrict the strength of prescriptive statements and transferability claims.

LIMITATIONS

This review is bounded by the supplied baseline article and bibliographic export. Full texts, the complete database query, search date, screening log, independent-review records, and a study-level quality file were unavailable. Consequently, the review cannot provide a reproducible PRISMA count, formal risk-of-bias judgments, or verified distributions by country, income group, setting, waste stream, intervention, and study design. Abstracts also provide insufficient detail to establish causal effects, long-term financial performance, market durability, worker displacement, or operational resilience.

The corpus is heterogeneous and recent. Reviews, cases, surveys, models, and experiments answer different questions and use different boundaries. The article therefore offers a design-sensitive narrative synthesis and an explicitly propositional framework; it does not pool effects, rank technologies universally, or claim regional representativeness. A future update should reproduce the search, retrieve full texts, apply design-specific appraisal tools, double-screen records, publish the extraction matrix, and test the proposed relationships with longitudinal municipal data.

CONCLUSIONS

The reviewed literature supports a shift from facility-centered planning toward the governance of an end-to-end public-service and material-flow chain. Circular and digital interventions appear most credible when collection is reliable, separated materials retain quality, responsibilities are enforceable, life-cycle costs are affordable, recovered products have outlets, and workers and affected communities share in decision-making and benefits.

The proposed context-conditioned framework is a synthesis and research agenda, not a validated transition law. It directs attention to three recurring tensions: ambition versus service reality, optimization versus institutional data capacity, and aggregate efficiency versus justice. These tensions explain why similar technologies may produce different outcomes across municipalities and why regional examples should not be generalized without corpus-level evidence.

For practice, the defensible implication is cautious sequencing and explicit testing of enabling conditions rather than universal technology prescriptions. For research, the priority is stronger traceability: reproducible searches, full-text and design-specific quality appraisal, closed mass balances, longitudinal implementation evidence, distributional indicators, and climate-stress testing. These improvements would allow future reviews to distinguish promising mechanisms from durable municipal performance.

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