

Integrated Solid Waste Management: Challenges, Technologies, and Sustainable Solutions

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Abstract

The exponential growth of urban populations, coupled with rising consumption and industrialisation, has made solid waste one of the most pressing environmental challenges of the 21st century. This review examines Integrated Solid Waste Management (ISWM) as a holistic framework that combines waste prevention, collection, treatment, resource recovery, and final disposal into a coordinated system tailored to local social, economic, and institutional conditions. It begins by characterising municipal solid waste generation and composition across different income settings, highlighting how organic content and recyclable fractions shift with urbanisation and affluence. Key challenges are then discussed, including inadequate collection coverage, poor source segregation, financial and institutional constraints, and the environmental and public-health consequences of unmanaged waste. The review surveys the principal treatment technologies available within the ISWM hierarchy composting, anaerobic digestion, material recovery facilities, incineration and waste-to-energy systems, and engineered sanitary landfilling comparing their suitability, advantages, and limitations. Attention is also given to enabling policy instruments such as extended producer responsibility, public-private partnerships, and integration of the informal recycling sector, as well as the role of public participation in sustaining behaviour change. The study concludes by situating ISWM within a circular-economy framework and outlining emerging trends including chemical recycling, AI-assisted sorting, and landfill-gas-to-energy technologies that are likely to shape the future of sustainable waste management.

Keywords: Integrated Solid Waste Management; Municipal Solid Waste; Waste-to-Energy; Circular Economy; Recycling; Sanitary Landfilling; Sustainable Waste Solutions

1. Introduction

Solid waste generation is an inevitable consequence of human activity, and its scale has grown enormously with rising population, urbanisation, industrialisation, and changing consumption patterns. Globally, cities generate over two billion tonnes of municipal solid waste (MSW) every year, and this figure is projected to rise substantially over the coming decades as developing economies urbanise and per-capita consumption increases. Left unmanaged, solid waste poses serious threats to public health, environmental quality, and climate stability, contributing to soil and water contamination, greenhouse gas emissions, vector-borne disease, and degradation of urban aesthetics and liv The exponential growth of urban populations, coupled with rising consumption and industrialisation, has made solid waste one of the most pressing environmental challenges of the 21st century. This chapter examines Integrated Solid Waste Management (ISWM) as a holistic framework that combines waste prevention, collection, treatment, resource recovery, and final disposal into a coordinated system tailored to local social, economic, and institutional conditions (Jebaranjitham et al., 2022). It begins by characterising municipal solid waste generation and composition across different income settings, highlighting how organic content and recyclable fractions shift with urbanisation and affluence. Key challenges are then discussed, including inadequate collection coverage, poor source segregation, financial and institutional constraints, and the environmental and public-health consequences of unmanaged waste. The chapter surveys the principal treatment technologies available within the ISWM hierarchy composting, anaerobic digestion, material recovery facilities, incineration and waste-to-energy systems, and engineered sanitary landfilling comparing their suitability, advantages, and limitations. Attention is also given to enabling policy instruments such as extended producer responsibility, public-private partnerships, and integration of the informal recycling sector, as well as the role of public participation in sustaining behaviour change. The chapter concludes by situating ISWM within a circular-economy framework and outlining emerging trends including chemical recycling, AI-assisted sorting, and

landfill-gas-to-energy technologies that are likely to shape the future of sustainable waste management (Singh et al., 2024).

Integrated Solid Waste Management (ISWM) has emerged as the dominant paradigm for addressing these challenges. Rather than relying on a single method of disposal, ISWM combines a hierarchy of complementary strategies waste prevention, reduction, reuse, recycling, biological and thermal treatment, and environmentally sound disposal selected and combined according to local environmental, economic, social, and institutional conditions. This chapter examines the fundamental challenges confronting solid waste management systems, surveys the principal technologies available for waste treatment and resource recovery, and discusses pathways toward sustainable, circular-economy-aligned solutions (Harbiankova and Kalinowski, 2023).

2. Waste generation and Characterization

Effective planning of any waste management system begins with a reliable understanding of how much waste is generated and what it consists of. Waste generation rates vary widely across regions, driven primarily by income level, urbanisation, climate, and cultural consumption habits. High-income countries typically generate more waste per capita, but this waste tends to contain a smaller organic fraction and a larger share of packaging materials, paper, and plastics (Zhang et al., 2024). Low- and middle-income countries generate less waste per person on average, but the organic fraction is considerably higher, and collection coverage is often incomplete.

Waste characterization determining the physical composition, moisture content, calorific value, and density of the waste stream is essential for selecting appropriate treatment technologies. A waste stream dominated by organic matter is well suited to composting or anaerobic digestion, whereas a stream rich in dry combustible material may be better suited to energy recovery. Table 1 summarises typical municipal solid waste composition across income categories (Ezeudu et al., 2024).

Table 1. Typical Municipal Solid Waste Composition by Country Income Group

Waste category	Low-income countries (%)	Lower-middle-income countries (%)	Upper-middle-income countries (%)	High-income countries (%)	References
Food and green waste	56	53	54	32	(Sharma and Jain, 2020)
Paper and cardboard	7	12.5	12	25	(Ezeudu et al., 2024).
Plastic	6.4	11	11	13	(Ezeudu et al., 2024).
Glass	1	3	4	5	(Ezeudu et al., 2024).
Metal	2	2	2	6	(Sharma and Jain, 2020)
Rubber and leather	<1	<1	1	4	(Sharma and Jain, 2020)
Wood	<1	1	1	4	(Ezeudu et al., 2024).
Other	27	17	15	11	(Ezeudu et al., 2024).
Total	≈100	≈100	≈100	100	(Sharma and Jain, 2020)

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As shown in Table 1, the organic fraction declines steadily as income rises, while recyclable dry fractions such as paper, plastic, and glass increase. This pattern has direct implications for technology choice: low-income cities may derive the greatest benefit from composting and organic-waste diversion, while high-income cities have greater potential for material recovery and recycling-based interventions.

3. Challenges in Solid Waste Management

3.1 Rapid Urbanisation and Rising Waste Volumes

Urban population growth continues to outpace the expansion of waste management infrastructure in many regions, particularly in low- and middle-income countries. This mismatch results in overburdened collection systems, uncollected waste accumulating in public spaces and waterways, and pressure on already-limited landfill capacity (Powell et al., 2018).

3.2 Inadequate Collection and Segregation

A large share of waste-related environmental and health problems stems not from a lack of treatment technology but from insufficient collection coverage and the absence of source segregation. Without separation of organic, recyclable, and residual fractions at the household or institutional level, downstream treatment options become more costly, less efficient, and in some cases infeasible (Gajera et al., 2026).

3.3 Financial and Institutional Constraints

Solid waste management is typically the responsibility of local governments, which frequently lack the financial resources, technical capacity, and institutional coordination required to operate modern systems. Tariff structures often fail to recover the full cost of service, and waste management competes with other urban priorities for limited municipal budgets (Filimonova and Birchall, 2024).

3.4 Environmental and Public Health Impacts

Open dumping and uncontrolled burning still common practices in many regions release methane, particulate matter, dioxins, and furans, while contaminating soil and groundwater through uncontrolled leachate. Poorly managed waste sites also serve as breeding grounds for disease vectors and are frequently linked to occupational hazards faced by informal waste pickers (Abubakar et al., 2022).

3.5 Technological and Infrastructure Gaps

Advanced treatment technologies such as waste-to-energy plants and engineered sanitary landfills require significant capital investment, skilled operating personnel, and consistent electricity or feedstock supply conditions that are not always present, particularly in smaller or resource-constrained municipalities (Soni et al., 2025).

4. Waste Collection, Segregation, and Transportation

Collection and transportation typically account for the largest share often 50 to 80 percent of total municipal solid waste management costs, making logistical efficiency a critical determinant of system sustainability. Modern ISWM systems increasingly rely on route optimisation software, geographic information systems (GIS), and telematics-enabled fleet tracking to reduce fuel consumption and collection time. Source segregation, typically implemented through a two-bin (wet/dry) or three-bin (wet/dry/hazardous) system, is widely regarded as the foundation of an effective ISWM programme, since it directly determines the quality and value of materials available for downstream recycling or composting. Transfer stations play a complementary role by consolidating waste from collection vehicles into larger transport units, reducing the number of trips required to reach distant treatment or disposal facilities (Wu et al., 2020).

5. Waste Treatment and Resource Recovery Technologies

A wide portfolio of treatment technologies is available within the ISWM framework, each suited to particular waste fractions, scales of operation, and local conditions. Table 2 compares the principal technologies in terms of suitable waste streams, advantages, limitations, and relative capital and operating cost.

Table 2. Comparative Overview of Solid Waste Treatment Technologies

Treatment technology	Basic principle	Suitable waste/feedstock	Major products/resource recovery	Environmental considerations	Role in integrated SWM	References
Recycling / Material Recovery	Physical separation, processing and re-manufacturing of recyclable materials	Paper, cardboard, plastics, metals, glass	Secondary raw materials	Generally, reduces resource extraction and disposal impacts; contamination can reduce recovery efficiency	High priority for recyclable fractions	(Xu et al., 2007)
Composting	Controlled aerobic biological decomposition of biodegradable organic matter	Food waste, garden waste, agricultural residues, paper/cardboard and other biodegradable materials	Compost/soil amendment	Reduces organic waste entering landfills and can return nutrients and carbon to soil	Important biological treatment for source-separated organics	(Wu et al., 2020)
Anaerobic Digestion (AD)	Microbial decomposition of organic matter under oxygen-free conditions	Food waste, market waste, manure, fats/oils/grease and other biodegradable materials	Biogas + digestate	Methane can be captured for energy rather than released; digestate requires appropriate management	Resource recovery + energy recovery	(Xu et al., 2007)
Incineration / Waste-to-Energy	Controlled thermal combustion of combustible waste, generally with energy recovery	Mixed combustible MSW, refuse-derived fuel and selected high-calorific wastes	Heat, steam and electricity; bottom ash and other residues	Air emissions and ash management require stringent controls	Thermal treatment for suitable residual waste	(Wu et al., 2020)
Gasification	Thermochemical conversion of carbonaceous waste with limited oxygen/oxidant	Selected combustible, relatively homogeneous or prepared waste/RDF	Producer gas/syngas, heat and potentially fuels/chemicals	Requires effective gas cleaning and residue management	Advanced thermal recovery	(Jayanarashimhan et al., 2024)

Pyrolysis	Thermal decomposition in the absence of oxygen	Selected plastics, biomass and relatively homogeneous prepared waste	Pyrolysis oil, gases and char	Emissions depend strongly on feedstock and process controls	Advanced resource/energy recovery	(Xu et al., 2007)
Mechanical–Biological Treatment (MBT)	Mechanical sorting combined with biological stabilization of the organic fraction	Mixed municipal solid waste	Recyclables, stabilized organic fraction, RDF/SRF and residual waste	Can reduce biodegradable material going to landfill; rejects still require final management	Integrated pre-treatment and recovery system	(Jayanarashimhan et al., 2024)
Sanitary Landfill	Engineered containment and controlled disposal of residual waste using liners, leachate management and gas control	Non-recyclable and non-recoverable residual MSW	Potential landfill gas; recovered land after closure	Methane generation and leachate require careful control; landfill gas can be captured for energy	Final disposal route for unavoidable residuals	(Jayanarashimhan et al., 2024)
Landfill Gas Recovery	Collection and utilization of methane generated during anaerobic decomposition in landfills	Biodegradable waste already deposited in landfill	Biogas/methane, electricity or heat	Reduces uncontrolled methane emissions when effectively captured and utilized	Energy recovery from existing landfill infrastructure	(Xu et al., 2007)

5.1 Biological Treatment

Composting and anaerobic digestion are the two dominant biological treatment routes for the organic fraction of MSW. Composting is an aerobic process that converts biodegradable material into a stable, humus-like soil conditioner over several weeks, while anaerobic digestion breaks down organic matter in the absence of oxygen to produce biogas a renewable energy source alongside a nutrient-rich digestate (Czekala et al., 2023).

5.2 Thermal Treatment and Waste-to-Energy

Thermal technologies, including mass-burn incineration, pyrolysis, and gasification, convert the combustible fraction of waste into heat, electricity, or synthetic fuels. Modern waste-to-energy facilities are equipped with flue-gas cleaning systems to control emissions of particulates, acid gases, and dioxins, and can reduce waste volume by approximately 90 percent while generating recoverable energy (Sarker et al., 2024).

5.3 Recycling and Material Recovery Facilities

Material Recovery Facilities (MRFs) mechanically and manually sort commingled dry recyclables paper, plastic, metal, and glass into distinct material streams for sale to secondary manufacturing industries. The efficiency of an MRF depends heavily on the quality of upstream segregation and the presence of stable markets for recovered materials (McKendry, 2024).

6. Engineered landfilling and final disposal

Even the most advanced ISWM systems generate a residual fraction that cannot be economically recycled, composted, or thermally treated, making some form of final disposal unavoidable. Sanitary landfilling engineered with impermeable liners, leachate collection and treatment systems, and controlled gas capture remains the standard method for managing this residual stream and represents a substantial improvement over open dumping in terms of groundwater protection and methane control. Where feasible, captured landfill gas can itself be used for electricity generation, converting a liability into a modest renewable energy resource (Kulkarni, 2020).

7. Policy, Regulatory, and Institutional Frameworks

Technology alone cannot resolve solid waste challenges without an enabling policy and institutional environment. Effective ISWM systems are typically underpinned by extended producer responsibility (EPR) regulations that shift a share of end-of-life management costs onto product manufacturers; landfill diversion targets and taxes that discourage disposal in favour of higher-order hierarchy options; and clear allocation of institutional responsibility among national, regional, and municipal authorities (Kurniawan et al., 2020).

Public-private partnerships (PPPs) have become an increasingly common mechanism for mobilising capital and technical expertise, particularly for capital-intensive infrastructure such as waste-to-energy plants and engineered landfills. Equally important is the formal integration of the informal recycling sector waste pickers and small-scale recyclers who, in many developing-country cities, already recover a significant share of recyclable material into official systems through cooperatives, identity recognition, and fair pricing arrangements.

8. Public participation, awareness and behaviour change

The success of source segregation, waste reduction, and recycling programmes ultimately depends on the willingness of households, businesses, and institutions to change established waste-handling behaviours. Sustained public awareness campaigns, school-based environmental education, and community-level incentive schemes (such as pay-as-you-throw tariffs or deposit-refund systems) have all been shown to meaningfully improve segregation rates and reduce contamination of recyclable streams. Behaviour change is generally most durable when combined with visible, convenient service improvements, so that citizens experience a direct and immediate benefit from compliance (Etim, 2024).

9. Towards Sustainable Solutions: The Circular Economy Approach

A circular economy approach reframes waste not as an end-of-life burden but as a potential resource to be kept in productive use for as long as possible. Applied to solid waste management, this means prioritising design-for-recyclability, extended product life, and closed-loop material recovery over end-of-pipe disposal (Rhaman et al., 2025). Figure 1 illustrates the waste management hierarchy that underlies this approach, ranking strategies from the most to the least environmentally preferable.

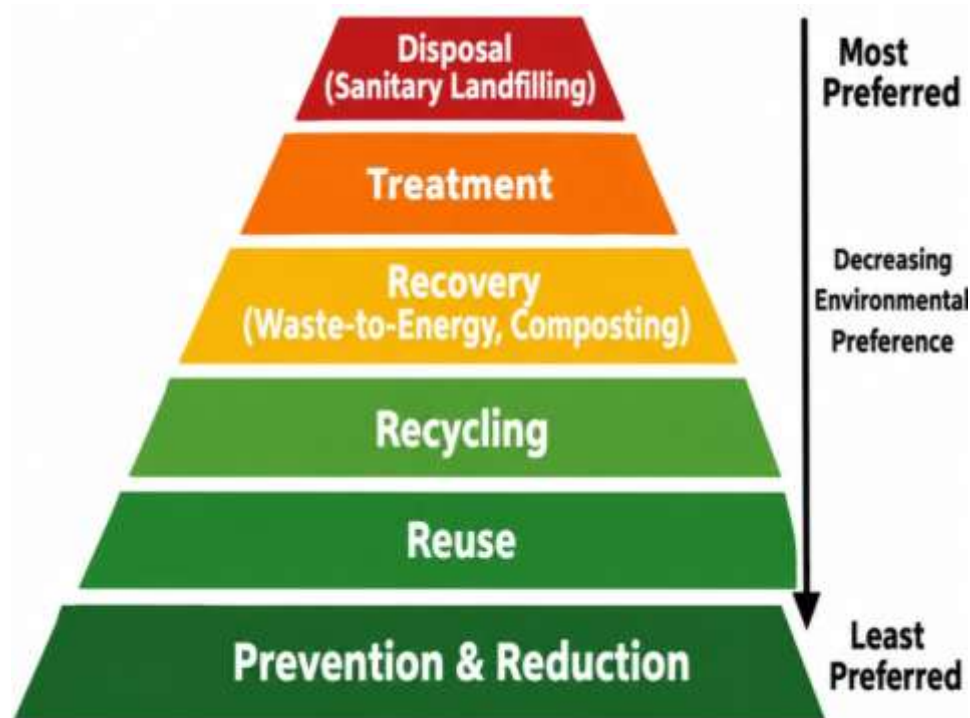


Figure 1. The Integrated Solid Waste Management Hierarchy, ranked from most to least preferred strategy.

Key elements of a circular, sustainable ISWM strategy include: Decentralised composting and biogas plants that treat organic waste close to its point of generation, reducing transport costs and emissions. Extended producer responsibility schemes that make manufacturers financially and physically responsible for packaging and product end-of-life. Integration of informal-sector waste pickers into formal recycling value chains, improving both recovery rates and livelihoods. Investment in waste-to-energy and refuse-derived fuel (RDF) facilities to recover value from the non-recyclable combustible fraction. Digital tools GIS-based route optimisation, IoT-enabled smart bins, and data-driven monitoring to improve operational efficiency and transparency. Regional and cluster-based facility planning, allowing smaller municipalities to share the capital cost of advanced treatment infrastructure (Mandpe et al., 2022).

10. Conclusion and Future Perspectives

Integrated Solid Waste Management represents a necessary shift away from single-technology, disposal-centric approaches toward a systems-level strategy that combines prevention, resource recovery, and environmentally sound disposal in proportions tailored to local conditions. The evidence reviewed in this study underscores that no single technology whether composting, anaerobic digestion, incineration, or landfilling is universally optimal; rather, sustainable outcomes depend on matching waste characteristics, financial capacity, and institutional strength to an appropriately integrated mix of solutions. Looking ahead, several trends are likely to shape the future trajectory of solid waste management. Climate policy is expected to place growing pressure on landfill methane emissions, accelerating investment in organic-waste diversion and landfill gas capture. Advances in chemical recycling and plastic-to-fuel pyrolysis technologies promise to expand the range of materials that can be recovered rather than discarded, addressing a fraction of the waste stream that has historically resisted conventional recycling. Digitalisation including AI-assisted sorting robots in MRFs, blockchain-based material traceability, and IoT-enabled fill-level sensors for collection optimisation is poised to substantially improve the efficiency and transparency of waste systems. Finally, the continued mainstreaming of extended producer responsibility and circular-economy policy frameworks is likely to shift greater responsibility upstream, toward product and packaging design, reducing the burden placed on downstream waste management infrastructure altogether. Realising this future will require sustained investment, supportive regulation, and perhaps most importantly active engagement of citizens as partners rather than passive recipients of waste management services.

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