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Waste-to-value Opportunity and Challenges

1.1 Introduction

Rapid economic growth and urbanization worldwide have resulted in a substantial increase in resource consumption and waste generation. Disposing of this growing volume of solid waste, particularly in landfills, is often neither economically feasible nor sustainable in urban environments. Energy recovery from waste, resource recovery, and waste volume reduction represent attractive and viable alternatives for waste management. Extracting energy from waste minimizes the need for energy produced from finite resources. Therefore, there is an urgent need to develop sustainable strategies for waste management. This study explores the latest advancements in sustainable waste-to-energy (WtE) technologies, resource recovery methods, and low-carbon biotechnologies and bioenergy options. Recent research highlights the growing importance of the circular economy as a sustainable waste management approach [1, 2]. WtE alternatives are crucial in the waste management sector. This chapter presents an innovative approach focused on addressing the challenges of managing organic waste by integrating WtE technologies. Globally, there is increasing emphasis on sustainable waste management practices, as utilizing organic waste for WtE purposes is a viable option. Identifying and prioritizing WtE alternatives is key, given the large quantities of waste in the management system. The goal is to reduce the environmental and logistical impacts of organic waste disposal, contributing to a more efficient and sustainable waste management system aimed at minimizing environmental effects and producing renewable energy. Ludlow et al. [3] emphasize that achieving net-zero greenhouse gas (GHG) emissions by 2050 fundamentally requires a shift in waste management practices. Organic waste disposal frequently presents significant challenges, including insufficient collection infrastructure, limited public awareness, and operating difficulties, particularly in urban areas. Daily per capita waste generation varies considerably globally, ranging from 0.11 to 4.54 kg [4].

Managing waste involves complexity and costs, which differ depending on local resource allocation and population density. However, as waste volume and disposal costs rise, developing countries face significant challenges in managing waste

effectively [5]. Despite these challenges, alternative waste management options, such as anaerobic digestion (AD), pyrolysis, and gasification, are gaining traction. Implementing effective waste management practices and technologies is critical for mitigating negative environmental and health impacts [6]. Developing nations urgently need to adopt sustainable waste management practices.

1.1.1 Waste-to-energy

WtE technologies are commonly employed for sustainable waste management, facilitating simultaneous energy generation and effective disposal [7]. Among WtE methods, thermal conversion is the most widely adopted approach for large-scale waste-processing. Incineration, a thermal technology, is still under development; while pyrolysis remains experimental, it is not yet commercially viable for managing municipal solid waste (MSW) globally. Biological conversion methods like AD are also used, particularly for bio-methanization. AD is frequently utilized for processing organic-rich biodegradable waste like manure and sewage sludge [8]. Using landfills for waste disposal is less favored due to drawbacks such as unpleasant odors, GHG emissions from methane (CH₄), leachate production, and associated health risks. Evidence suggests that WtE technologies implemented in Latin American and Caribbean (LAC) countries offer long-term advantages, including economic development, environmental benefits, and improved human well-being [9]. Existing literature provides a detailed look at the scale of waste challenges in developing nations and explores potential methods to promote sustainable waste management practices in the future.

This chapter helps fill knowledge gaps by analyzing treatment methods used in developing countries and their potential to support continuous sustainability by aligning with renewable energy sources such as hydroelectricity, which are environmentally friendly and non-emission-generating. For example, South Africa's electricity mix in 2021 heavily relied on coal-fired plants (84%), resulting in substantial CO₂ emissions of 396 g CO₂/kWh. Energy consumption also surged sharply in New Zealand (66 kg CO₂/kWh, primarily powered by geothermics [57%], hydro [17%], and thermal sources (9%)) [10, 11]. The rapid urbanization in many developing countries intensifies waste management challenges.

Nonetheless, these challenges also present significant opportunities. Treating waste as a valuable resource rather than a problem allows different nations to adopt sustainable waste management techniques and achieve future development goals. Studies conducted in Korea demonstrate how WtE operations reduced GHG emissions by 16,061 tCO₂eq annually; this reduction is projected to increase further to 26,477 tCO₂eq per year by 2021 [12]. The environmental advantages of WtE technologies (like incineration, pyrolysis, gasification, and incineration) vary depending on the specific method used [13]. The purpose of this chapter is to provide a systematic evaluation and highlight the benefits and challenges of WtE technology, especially in developing countries. This includes assessing the characteristics and volume of waste produced, current treatment methods, the opportunities and obstacles within the waste management sector, and the feasibility of implementing or expanding WtE solutions domestically.

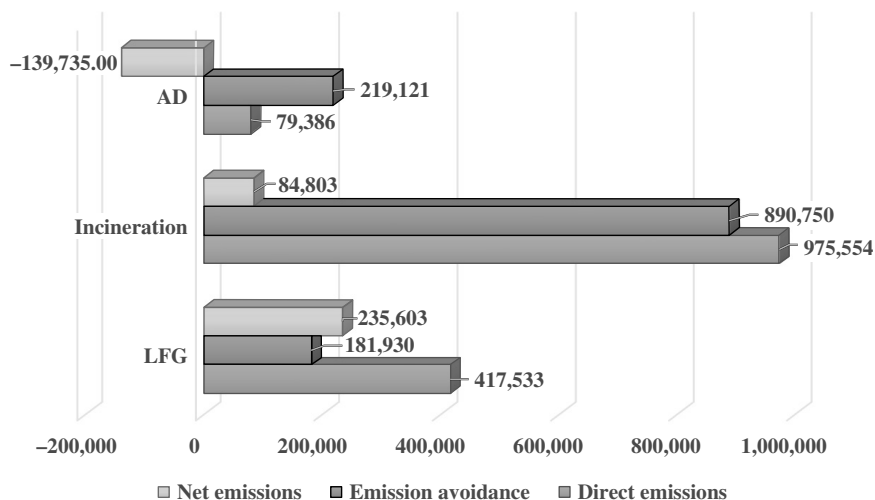


Figure 1.1 GHG emissions and emission saving from WtE technologies (tCO₂-eq/year). Adapted from [16].

1.1.2 Environmental Benefits

Figure 1.1 illustrates that incineration notably influences the global warming potential (GWP), contributing between 975,554 and 830,750 tCO₂-eq/year due to the large quantity of processed waste. In thermal technologies, emissions are a primary contributor to the GWP [14]. The environmental impact of incineration is largely dictated by its energy conversion efficiency; higher efficiency leads to lower emission rates. For instance, an incineration plant operating at 25% efficiency emits roughly 1,007 kg CO₂-eq per MWh of combustion, while increasing efficiency by just 5% (to 30%) reduces emissions by approximately 17% due to lower GHG emissions [15]. The significant emission reductions from incineration can be attributed to the characteristics of the burned materials. Plastic waste, comprising over 20% of facility input, has the most notable impact on GWP due to its chemical properties and low moisture content, resulting in greater emission contributions [16]. Moreover, the common practice of disposing of MSW without source separation leads to high moisture levels [17]. Achieving greater environmental and economic benefits from WtE technologies requires continuous improvements.

1.1.3 Energy Generation Potential

Uncollected CH₄ (25%) from landfill gas (LFG) is a major factor contributing to GWP, amounting to 417,533 tCO₂-eq/year of GHG emissions [18]. In contrast, AD methods produce the lowest emissions, achieving 99% efficiency in capturing CH₄, leaving only 5% to be released into the atmosphere. The environmental performance of WtE technologies compared to coal-based electricity generation was also examined [19]. Research indicates that LFG recovery results in the highest net GWP, estimated between 137,439 and 323,604 tCO₂-eq annually. Incineration shows a

lower GWP, ranging from 219,121 to 84,803 tCO₂-eq/year. Incineration with energy recovery surpasses simple incineration in reducing emissions. Energy generation from WtE can offset some of the benefits gained from electricity production but significantly counteracts global warming effects. AD technology has substantially reduced impact on GWP, resulting in an avoidance of 95,321–195,395 tCO₂-eq/year of GHGs. From an environmental standpoint, AD technology is arguably the most suitable option due to its lower emissions.

1.1.4 Economic Potential

The global waste recycling services market is projected to reach US\$99.2 billion by 2032, with an average annual growth rate of 5.1% from 2023 to 2032 [20]. In 2022, the Asia-Pacific region's waste recycling services market constituted over 80% of the total market share. The US Environmental Protection Agency (EPA) reports that the recycling industry employs 534,000 people and contributes US\$13.2 billion in wages and benefits [15]. An analysis indicates that in 2020, only 9% of electronic waste (e-waste) was properly collected and recycled [21]. According to the EPA, the United States generated 292.4 million tons of MSW in 2018, of which 69 million tons were recycled [22]. The increasing adoption of advanced WtE technology offers substantial potential for adding value to waste and generating energy [23]. The precise potential varies based on factors such as the type and volume of available waste, technological readiness, environmental considerations, and government policies. Figure 1.2 illustrates potential applications of waste recycling and processing technologies that significantly influence the waste recycling services market value.

WtE presents considerable potential, but its viability is dependent on various factors including public acceptance, regulatory frameworks, technological maturity, and economic feasibility. WtE initiatives should be driven by efforts to generate waste, recover resources, and explore renewable energy sources to establish a truly sustainable waste management system.

Comparing WtE options involves evaluating different technologies and strategies for converting waste into energy. Figure 1.3 provides a comparative analysis of common WtE approaches.

The selection of a WtE option is influenced by factors such as waste composition, local regulations, infrastructure availability, energy demand, environmental impacts, and economic viability. Often, a combination of technologies is utilized to maximize resource recovery and energy generation while minimizing environmental effects. While WtE has shown notable advancements in waste management and energy production, recognizing that the most suitable approach is dependent on local circumstances, waste characteristics, technological readiness, and environmental factors is important. Therefore, the reasons for favoring WtE are often multifaceted:

- 1. Waste Reduction:** WtE facilities substantially decrease the volume of waste sent to landfills by converting it into energy, thereby prolonging the lifespan of existing landfill sites and lessening the need for new ones [26].
- 2. Energy Production:** WtE plants generate electricity or heat from burning MSW, biomass, or other waste sources, diversifying energy supply and meeting local energy demands.

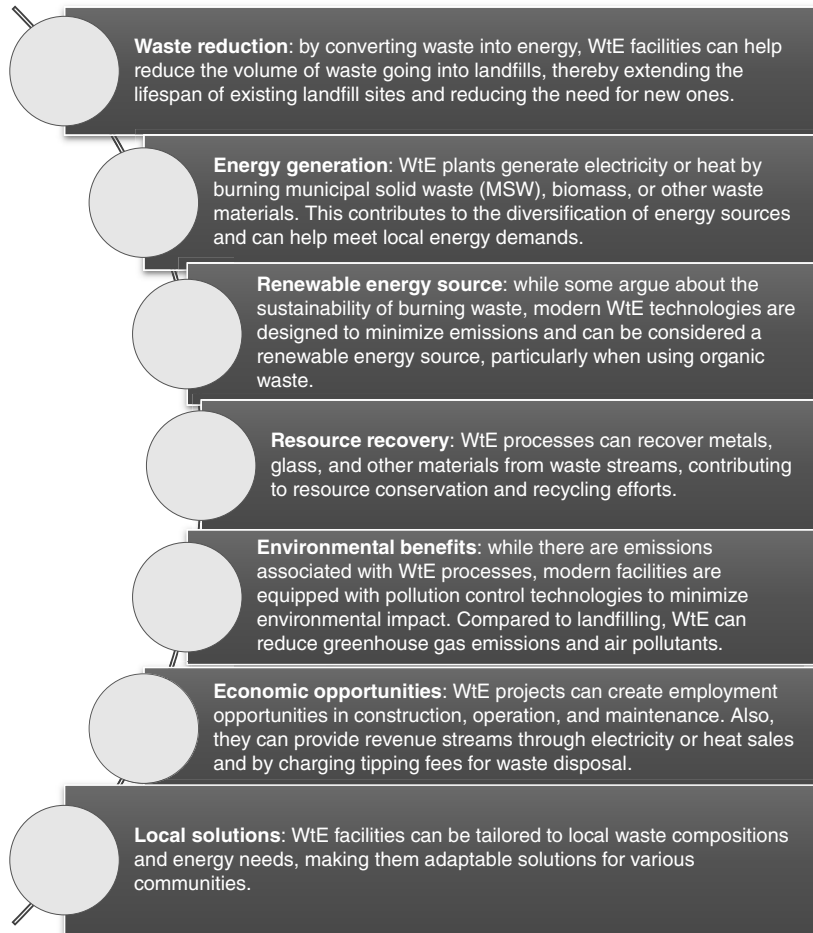


Figure 1.2 Potential of waste-to-energy (WtE) technology. Adapted from [24].

- 3. Resource Recovery:** WtE processes can recover valuable materials like metals and glass from waste, supporting resource conservation and recycling efforts.
- 4. Environmental Benefits:** WtE facilities are equipped with pollution control technologies to minimize harmful emissions. Compared to landfilling, WtE can reduce GHG emissions and air pollutants.
- 5. Renewable Energy Source:** Depending on the type of waste processed, WtE can be considered a renewable energy source, especially when using organic waste.
- 6. Job Creation:** WtE facilities create employment in construction, operation, and maintenance, benefiting local economies.
- 7. Local Solutions:** WtE facilities can be customized to local waste streams and energy needs, providing flexible options for different communities.

However, acknowledging the complexity of waste management and the lack of a single solution for every situation is crucial. Effective implementation of sustainable waste management strategies, such as sorting, recycling, composting, and other

<p>Incineration:</p> <ul style="list-style-type: none"> ◦ Process: involves combusting waste at high temperatures in a controlled environment. ◦ Energy output: generates heat, which can be used for electricity generation or district heating. ◦ Advantages: mature technology, high energy recovery efficiency, reduces waste volume, can handle various types of waste. ◦ Challenges: concerns about air emissions (though modern facilities have advanced pollution control systems), high initial investment costs, public perception, and acceptance issues.
<p>Gasification:</p> <ul style="list-style-type: none"> ◦ Process: converts solid waste into synthetic gas (syngas) by reacting it with a controlled amount of oxygen and/or steam at high temperatures. ◦ Energy output: syngas can be used to produce electricity, heat, or biofuels. ◦ Advantages: can handle diverse feedstocks, potentially higher energy efficiency than incineration, lower emissions. ◦ Challenges: technically complex, requires preprocessing of waste, higher capital costs compared to incineration.
<p>Pyrolysis:</p> <ul style="list-style-type: none"> ◦ Process: involves heating waste in the absence of oxygen to produce bio-oil, gas, and char. ◦ Energy output: bio-oil can be used as a fuel, gas can be burned for energy, and char can be used for various applications. ◦ Advantages: can handle various types of waste, produces bio-oil suitable for transportation fuels or chemical feedstocks, potentially lower emissions. ◦ Challenges: technical challenges in scaling up, high capital costs, energy-intensive process.
<p>Anaerobic digestion:</p> <ul style="list-style-type: none"> ◦ Process: breaks down organic waste in the absence of oxygen by microorganisms to produce biogas (methane and carbon dioxide) and digestate (organic fertilizer). ◦ Energy output: biogas can be used for electricity generation, heat production, or vehicle fuel. ◦ Advantages: suitable for organic waste, produces renewable energy and organic fertilizer, reduces greenhouse gas emissions. ◦ Challenges: limited to organic waste streams, requires a steady supply of feedstock, biogas composition may vary.
<p>Landfill gas recovery:</p> <ul style="list-style-type: none"> ◦ Process: captures methane generated by the decomposition of organic waste in landfills and utilizes it for energy production. ◦ Energy output: methane can be used for electricity generation, heat production, or upgraded to natural gas quality. ◦ Advantages: utilizes existing landfill sites, reduces greenhouse gas emissions, relatively low capital costs. ◦ Challenges: dependent on landfill lifespan, requires significant infrastructure for gas capture and treatment.

Figure 1.3 Comparative analysis of some commonly used WtE techniques. Adapted from [25].

waste management methods, is essential. Furthermore, advancements in technology and continuous process optimization are necessary to determine the most appropriate waste management strategy for a given region or municipality.

1.2 Classification of Waste

Waste materials are classified based on various factors such as their composition, potential risks to human health and the environment, and relevant regulatory guidelines, as detailed below.

1.2.1 Hazardous Waste

Hazardous waste is defined as waste that poses significant risks to public health or the environment due to its inherent chemical, biological, or physical characteristics [6]. Waste materials are categorized as hazardous based on specific properties or origins, and regulations govern their handling. Key characteristics defined by regulatory bodies are as follows:

- **Ignitability:** Waste that can easily ignite, such as certain solvents, paints, and some types of oils.

- **Corrosivity:** Waste that is highly acidic or alkaline and can corrode containers, such as battery acid or specific cleaning agents.
- **Reactivity:** Waste that is unstable and can undergo violent reactions, release toxic gases, or explode under certain conditions, such as certain cyanide-containing wastes.
- **Toxicity:** Waste that contains substances harmful to human health or the environment, including heavy metals (like lead, mercury), pesticides, or certain industrial chemicals.

Specific hazardous wastes by Akpan et al. [27] are shown in Figure 1.4.

- **F-list:** Wastes from common manufacturing and industrial processes, such as specific solvents and wastewater.
- **K-list:** Wastes from specific industries (e.g., chemical manufacturing, pulp and paper industry), including sludges and residues from metal production.
- **P- and U-list:** Discarded commercial chemical products that are unused, off-specification, or spilled, including certain pesticides and laboratory chemicals.
- **Mixed Waste:** Waste containing both hazardous and radioactive components, often found in certain medical or research laboratories.
- **Medical Waste:** Waste generated by healthcare facilities, including contaminated sharps, materials soaked in blood, and expired medications.
- **Radioactive Waste:** Waste contaminated with radioactive materials, such as those from nuclear power generation, specific medical treatments, and research activities.
- **E-waste:** Discarded electronic devices containing hazardous substances like lead, mercury, and brominated flame retardants.

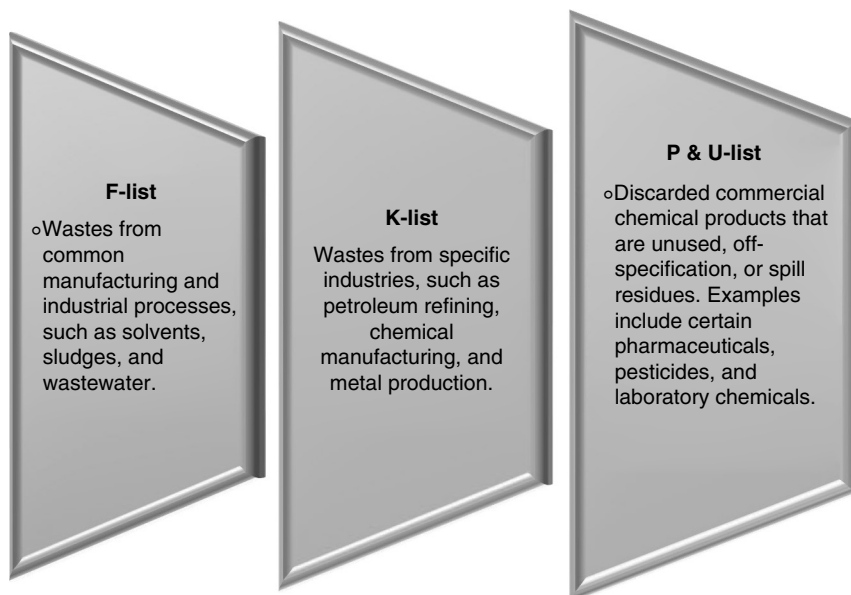


Figure 1.4 Category of hazardous wastes according to US EPA. Adapted from [27].

Table 1.1 Impact of hazardous waste on human health. Adapted from [28].

Toxic materials present in hazardous waste	Source of origin	Impact on human health
Cadmium	Battery waste/mining/fertilizer industries	Pulmonary diseases, liver and kidney damages, carcinogenic, skeletal/cardiovascular disorder
Manganese	Mining region	Neuropsychiatric disorder/respiratory diseases
Nickel	Mining/metal refining	Gastrointestinal system damage/lung or nasal cancer
Hydrocarbons	Industries of petrochemical	Nausea, bone marrow damage, headaches, nausea
PCBs	E-waste/fluorescent light/hydraulic fluid	Gastrointestinal/skin damage, carcinogenic
Pesticides	Insecticides	Stillbirths, carcinogenic, immune system disorder

Exposto et al. [28] documented adverse health effects in humans caused by exposure to toxic compounds in hazardous wastes, as presented in Table 1.1.

According to Saleh et al. [29], hazardous wastes are further categorized into special classes under specific regulations, even if they don't meet standard characteristics or appear on lists. Examples include medical waste, radioactive waste, and e-waste.

- **Medical Waste:** Waste generated by healthcare facilities, including contaminated sharps, materials soaked in blood, and expired medications.
- **Radioactive Waste:** Waste contaminated with radioactive materials, such as waste from nuclear power plants, specific medical treatments, and research materials.
- **E-waste:** Discarded electronic devices containing hazardous substances like lead, mercury, and brominated flame retardants.

Proper management of hazardous waste is crucial to prevent environmental contamination and protect human health. Regulations govern its generation, storage, transportation, treatment, and disposal to minimize risks. This often involves labeling, secure storage, specialized handling procedures, and disposal at authorized facilities equipped to manage hazardous materials safely.

1.2.2 Non-hazardous Waste

Non-hazardous waste is waste that does not pose significant risks to human health, or the environment based on its chemical, biological, or physical properties. This category encompasses various materials that can be safely disposed of in standard landfills or recycled without special handling procedures [30]. Some common examples and categories of non-hazardous waste are general non-toxic waste (paper,

cardboard, plastic packaging, food scraps, wood, concrete, bricks, and textiles), recyclable waste such as paper, cardboard, glass, metals (aluminum, steel), e-waste and certain types of plastics, biodegradable organic waste like food scraps, yard waste (leaves, grass clippings), and other organic materials.

Regulatory bodies, such as the EPA in the United States or the European Environment Agency (EEA) in Europe, provide detailed criteria and guidelines for waste classification. These classifications are crucial for the correct handling, storage, transportation, and disposal of waste to minimize environmental and public health risks. Effective management of non-hazardous waste typically involves strategies like source reduction, recycling, composting, and landfill disposal in compliance with local regulations. Recycling and composting help reduce the volume of waste sent to landfills and conserve natural resources by recovering valuable materials for reuse. Additionally, initiatives promoting waste reduction and sustainable practices aim to minimize the overall environmental impact of waste generation.

1.3 Current Status in Waste Management

1.3.1 Waste Collection

As of early 2022, waste management methods and technologies continue to advance, influenced by increasing environmental awareness, regulatory demands, and progress in waste treatment and recycling. Waste collection methods vary considerably depending on location, infrastructure, regulations, and environmental factors. Usual waste collection practices [31] are as follows:

1. **Curbside Pickup:** A widely used method, especially in urban and suburban areas. Residents place separated waste (recyclables, organic waste, general trash) in designated containers or bags for collection on scheduled days. Waste management trucks collect and transport the waste to processing facilities.
2. **Drop-off Centers:** In some regions, residents transport their waste to central drop-off points. These centers often provide separate containers for different waste types, facilitating recycling and proper disposal.
3. **Composting Programs:** Many municipalities promote composting by offering residents compost bins or composting services. Organic waste (food scraps, yard trimmings) can be collected separately and processed into compost for gardening or landscaping use.
4. **Special Collection Services:** Some areas offer dedicated services for bulky items like furniture, appliances, or electronics that don't fit standard bins. Residents can arrange pickups or drop items off at specific locations.
5. **Hazardous Waste Collection:** Hazardous materials (batteries, paint, chemicals, e-waste) require special handling due to environmental and health risks. Many communities organize programs or events for the safe disposal of these items.
6. **Commercial Waste Collection:** Services for businesses, industrial facilities, and institutions differ from residential services. Commercial waste often requires specialized handling and uses larger bins or dumpsters.

7. **Recycling Programs:** Recycling collection is typically part of regular waste collection. Residents are encouraged to separate recyclables (paper, plastic, glass, metal) from general waste for collection and transport to recycling facilities.
8. **Public Awareness and Education:** There is growing emphasis on engaging the community and educating the public to promote waste reduction, recycling, and proper disposal. Effective collection practices include campaigns to inform residents about correct disposal methods, the importance of recycling, and strategies to reduce waste through composting and reuse initiatives. These efforts aim to raise awareness about waste generation's environmental impacts and encourage behavioral changes to minimize waste production and increase recycling rates.
9. **Technological Innovations:** Some waste management systems integrate technology, such as RFID tags on bins for tracking collection routes and optimizing efficiency, or smart sensors to monitor bin fill levels and schedule collections dynamically.
10. **Informal Waste Collection:** In some areas, informal waste collectors (scavengers or waste pickers) play a significant role by collecting recyclable materials from streets, dumps, or landfills for sale or reuse.

These practices aim to minimize environmental impact, promote sustainability, and efficiently manage waste to protect public health and the environment. The integration of technology with smart practices enhances efficiency and reduces collection burdens. Abubaker et al. [32] highlighted that many solid waste management practices involve combining household waste with commercial waste, which can contain hazardous substances during collection and handling, negatively impacting the environment. This process involves waste material collection, transportation, and disposal, which presents cost concerns globally. Literature from 1970 onwards shows that investing in waste collection equipment has resolved most technical problems related to SWM. Daily waste collection practices in high-, middle-, and low-income countries are compared in Table 1.2.

Furthermore, waste collection is a critical component of waste management worldwide. Various approaches and expenditures are adopted in developed and developing nations, as detailed in Table 1.2. Thus, the current state of waste collection involves:

1. **Efficiency and Optimization:** Waste collection services are increasingly adopting data-driven methods and technologies to optimize routes, schedules, and resource allocation. This includes using Geographic Information Systems (GISs), route optimization software, and real-time monitoring systems to improve efficiency and reduce costs.
2. **Smart Waste Management:** Smart waste management solutions, incorporating sensors, Internet of Things (IoT) devices, and data analytics are being deployed to monitor waste bin fill levels, optimize collection routes, and schedule pickups more effectively. These technologies help reduce unnecessary collections, minimize overflow, and enhance overall service quality.
3. **Separation at Source:** Many waste management programs emphasize source separation, where residents or businesses are encouraged to separate recyclable

Table 1.2 MSW collection practices commonly by country's economic development.

Activity	High-income countries	Low-income countries	Middle-income countries
Waste collection	Collection rate >90%. Transfer stations, compactors, and motorized trucks are commonly available. In design of system, volume of waste and aging collection workers is considered	Generally, it serves wealthy, business, and high-visibility areas. Overall collection <50%. Inefficient and infrequent	In residential areas, there is an improvement in collection and transportation. Mainly 50–80% collection, mechanization, large vehicle fleet, and transfer stations
Cost	Cost of collection <10% of budget, while treatment of intermediate waste is a large budget allocation. Community participation reduces costs and increases options for planners	Cost of waste collection is 80–90% of SWM budget. Government regulation of waste fees exists, but collection is insufficient, and a small budget portion is for disposal	Cost of collection is 50–80% of MSWM budget. Some national and local governments require waste fees and show innovation in collection methods. More collection fleets, mechanization, and disposal expenditure

materials, organic waste, and non-recyclable waste at the point of generation. Source separation facilitates more efficient processing and recycling downstream, reducing contamination and maximizing resource recovery.

4. **Specialized Collection Programs:** Municipalities and waste management companies are implementing specialized collection programs for hazardous waste, e-waste, bulky items, and other materials that require separate handling and disposal due to their potential environmental and health impacts.
5. **Integration of Sustainable Practices:** Eco-friendly practices such as composting, AD, and material recovery facilities (MRFs) are becoming more integrated into waste management systems to divert organic waste from landfills, recover valuable resources, and reduce GHG emissions.
6. **Innovations in Collection Vehicles:** Waste collection vehicles are evolving to incorporate cleaner and more efficient technologies, such as electric and hybrid propulsion systems, compressed natural gas (CNG), or biodiesel engines. These vehicles help reduce emissions, noise pollution, and dependency on fossil fuels [33].

According to Keerthana et al. [34], land pollution is primarily caused by garbage spillage. They proposed various existing methods for monitoring garbage. One such method is an advanced waste collection system that separates waste into wet, dry, and metallic categories, as shown in Figure 1.5. This system uses sub-bins for different waste types and a dual motor/tray mechanism. Waste is initially placed in a common tray, where an IR sensor detects its presence. A moisture sensor then activates, and if the moisture reading is high, the waste is classified as wet; otherwise, it's dry. The three bins are positioned below, and an ultrasonic sensor checks the

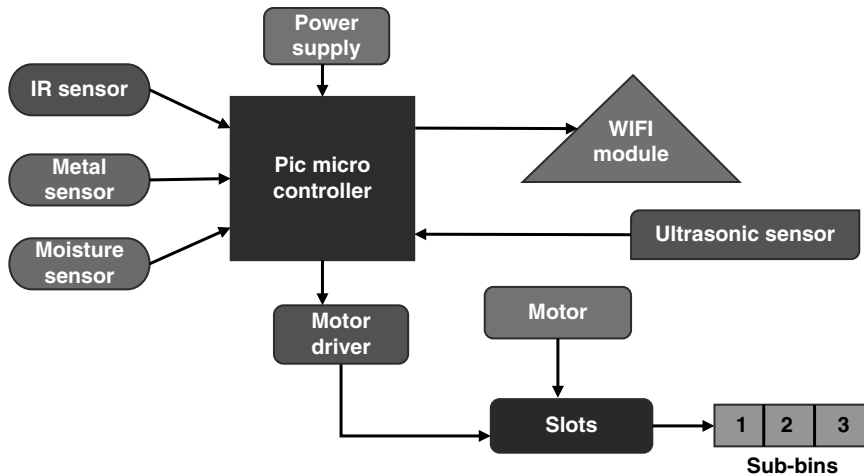


Figure 1.5 Block diagram of waste collection. Adapted from [34].

garbage level. The sensed data is transmitted via a PIC microcontroller. This entire process operates using an IoT application.

Overall, waste collection practices are increasingly focused on efficiency, sustainability, and innovation to address the challenges of waste management in an environmentally responsible manner while meeting the needs of growing urban populations.

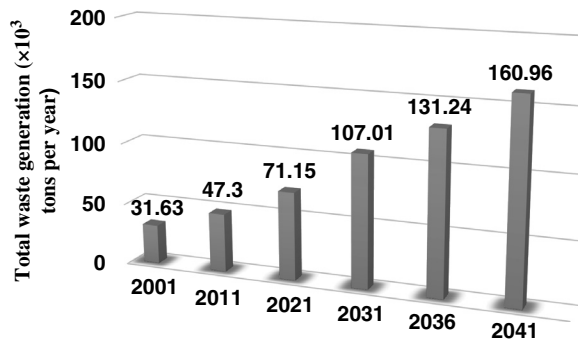
1.3.2 Waste Consolidation and Transportation

Waste transportation involves moving collected waste from its origin (homes, businesses, or drop-off centers) to various destinations for processing, recycling, or disposal. Kumar et al. [35] state that India faces primary challenges in waste management related to waste generation, inefficient collection, transportation, treatment, and disposal, with waste volumes increasing daily. As illustrated in Figure 1.6, it is estimated that by 2041, total waste generation will reach 160.95×10^3 tons per year, with the population projected to be approximately 595.4×10^6 . This suggests a per capita waste generation of around 0.741 kg/day. Since waste generation comes from various sources, including households, construction, organic matter, and agriculture, their collection, storage, and transportation are crucial aspects of waste management practices.

Here's a scenario illustrating waste transportation practices:

- **Consolidation:** After collection, waste is transported to a central transfer station or depot, where different types of waste are consolidated and loaded onto larger transport vehicles for efficient transport to processing facilities.
- **Recyclables:** Reusable materials (paper, plastic, glass, metal) are loaded onto separate trucks and transported to recycling facilities. These facilities may be located within or near the city, depending on contracts and logistics.

Figure 1.6 Total waste generation per year. Adapted from [35].



- **Organic Waste:** Organic waste from residential and commercial sources is transported to a composting facility. Specialized trucks are used, designed to handle organic material without odor or leakage during transit.
- **General Trash:** Non-recyclable and non-organic waste (residual household and commercial waste) is transported to a landfill or WtE plant. Trucks equipped with compaction mechanisms ensure efficient loading and transport to the designated facility.
- **Special Handling:** Hazardous materials from households and businesses (batteries, paints, chemicals) are transported separately to specialized treatment or disposal facilities equipped to safely handle hazardous waste.
- **Monitoring and Compliance:** Throughout transport, waste management authorities monitor vehicle routes, adherence to safety rules, and environmental standards. GPS tracking, electronic manifests, and regular inspections help ensure proper waste handling and transport.
- **Continuous Improvement:** Waste management authorities regularly evaluate and optimize transportation routes, vehicle fleet efficiency, and logistics to minimize costs, reduce environmental impact, and improve service delivery.

This scenario highlights the coordinated efforts involved in moving different types of waste from collection points to appropriate processing or disposal sites, aiming for effective waste management and environmental sustainability [36].

1.3.3 Waste Disposal Practices

A comprehensive approach is needed in order to manage large quantity of waste disposal in an energy efficient and environmentally friendly manner. Waste disposal practices involve the final stage of waste management, where waste is permanently removed from the environment through various methods [37]. Common waste disposal practices include:

1. **Landfilling:** Engineered landfills represent a primary method of waste disposal, designed with specific containment areas where waste is systematically deposited. Within these sites, the waste is typically compacted to reduce volume and subsequently covered with soil, a process often carried out daily or periodically. Contemporary landfill designs incorporate advanced environmental safeguards,

including impermeable liners and integrated systems for collecting leachate, the liquid that drains from waste, to prevent the contamination of surrounding groundwater and soil. Additionally, the anaerobic decomposition of organic matter within the contained waste mass produces LFG, which is primarily CH₄. Specialized collection systems are installed to capture this gas, which can then be either utilized for energy generation or safely flared, thus mitigating GHG emissions.

- 2. Incineration:** Waste incineration serves as a thermal treatment process involving the combustion of waste materials at elevated temperatures within controlled facilities. The primary objectives of this method are to significantly reduce the volume and mass of the waste stream. Furthermore, modern energy recovery facilities are often integrated with incinerators to capture the heat generated during this combustion process. This heat is typically used to produce steam, which subsequently drives turbines for electricity generation. To mitigate the environmental impact, these facilities are equipped with sophisticated air pollution control systems, such as scrubbers and filters, which are designed to minimize the emission of harmful substances including particulate matter, heavy metals, and dioxins into the atmosphere.
- 3. Composting:** Biological decomposition, specifically through composting, offers a viable treatment method for organic waste materials, including food scraps, yard trimmings, and paper products. This process is typically carried out in controlled environments where parameters such as moisture content, aeration, and temperature are carefully managed to optimize the microbial breakdown of organic matter. The outcome is the production of nutrient-rich compost. This valuable finished product can then be effectively applied as a soil amendment in various settings, including agriculture, landscaping, and erosion control initiatives, thereby enhancing soil health and promoting fertility.
- 4. Recycling:** This process constitutes a crucial waste management strategy focused on recovering valuable materials from discarded products. This process entails collecting and processing waste materials such as paper, plastics, glass, and metals to convert them into new products, thereby facilitating resource conservation and reducing the demand for virgin raw materials. Dedicated recycling facilities are equipped to sort, clean, and process these recyclable streams, transforming them into secondary raw materials or feedstocks suitable for various manufacturing industries. Furthermore, policy instruments like Extended Producer Responsibility (EPR) programs play a vital role by establishing manufacturer accountability for the collection and recycling of their products at the conclusion of their intended use phase.
- 5. Biological Treatment:** Bio-treatment methods leverage the metabolic activity of microorganisms to decompose organic waste, yielding valuable byproducts. Key techniques within this category include AD and aerobic digestion, which are employed to break down biodegradable materials. AD, conducted in the absence of oxygen, results in the production of biogas, primarily composed of CH₄, which can be harnessed for energy generation. In contrast, aerobic digestion utilizes oxygen to facilitate the biological decomposition of organic matter, typically yielding compost or other stable organic residues.
- 6. Hazardous Waste Treatment:** Hazardous waste, a category encompassing materials such as chemicals, solvents, heavy metals, and e-waste, necessitates

specialized treatment protocols due to the inherent and significant environmental and health risks associated with improper handling. The primary objective of hazardous waste treatment is to minimize these risks. Employed methods are diverse and may include chemical neutralization to alter hazardous properties, thermal processes like high-temperature incineration, or stabilization and immobilization techniques designed to render the waste less harmful or inert before final disposition.

7. **Waste-to-energy:** WtE facilities represent systems that convert waste materials into usable energy forms, including heat, electricity, or fuel. This conversion is achieved through a variety of thermal and biochemical processes. Advanced WtE technologies, such as gasification, pyrolysis, and plasma arc gasification, are capable of converting solid waste into syngas, a versatile intermediate product. This syngas can then be utilized directly for energy production or as a valuable chemical feedstock for further industrial processing.
8. **Secure Disposal:** Secure waste handling is a critical practice designated for specific waste streams, including medical waste, pharmaceuticals, and confidential documents, to ensure the prevention of unauthorized access and minimize the risk of environmental contamination. The methods employed for secure disposal are designed to guarantee safe handling and containment. These techniques may incorporate physical destruction processes such as shredding, biological neutralization through sterilization, or physical containment methods like encapsulation within specialized containers specifically designed for secure handling and ultimate disposition.

Agamuthu and Babel et al. [38] studied about SWM practices in Asia and pointed out that from last five decades, it was ranged over in Asia and identification of different challenges/issues were carried out. Since there is an increment in waste generation worldwide and concerning their disposal sites, most of the adopted disposal techniques are open dumps/landfills, which have become more widespread in low- or middle-income countries (79% south, 64% southeast, 51.1% south and central Asia) as summarized in Table 1.3.

Table 1.3 Distribution (%) of waste disposal techniques by different income level. Adapted from [38].

Waste management type	High-income countries (%)	Upper-middle-income countries (%)	Lower-middle-income countries (%)	Low-income countries (%)
Open dump	2	30	66	93
Landfill	39	54	18	3
Incineration	22	10	—	—
Composting	6	2	10	—
Other advanced methods	2	—	—	—
Recycling	29	4	6	3.7

Effective waste disposal practices aim to minimize environmental impact, conserve resources, and protect public health while meeting regulatory requirements and societal expectations for sustainable waste management.

1.3.4 Lack of Awareness

Limited awareness about waste treatment is a significant barrier to implementing sustainable waste management practices. In accordance with Hasan et al. [39], current human health problems and environmental degradation are due to lack of awareness and improper handling of waste. Various reasons for this lack of awareness and its potential consequences can be limited education, as communities may lack awareness of available waste treatment options and their importance. In some cultures or communities, there may be a lack of emphasis on proper waste management, leading to a mindset of disposability and indifference toward waste treatment practices. People may be unaware of the types of waste that can be treated and recycled, as well as the facilities and services available for waste treatment in their area. Without access to clear and accurate information, individuals may resort to improper disposal methods out of convenience or ignorance. Some individuals may perceive waste treatment options as too costly or inconvenient, particularly if they are accustomed to traditional disposal methods like landfilling or open burning. This perception can discourage people from seeking out and utilizing more sustainable waste treatment practices. Weak enforcement of waste management regulations can contribute to a culture of non-compliance and disregard for proper waste treatment practices. When there are no consequences for improper disposal, individuals may be less motivated to adopt responsible behaviors. Misinformation or misconceptions about waste treatment methods, such as the belief that certain materials cannot be recycled or composted, can lead to confusion and apathy among the public [40].

- **Limited Access to Infrastructure:** May be another reason, as in some regions, especially in rural or underserved areas, there may be a lack of infrastructure for waste treatment, such as recycling facilities or composting centers. Without access to these facilities, communities may resort to dumping or burning waste, exacerbating environmental pollution.

Addressing the lack of awareness for waste treatment requires a multi-faceted approach, including education, outreach, infrastructure development, regulatory enforcement, and community engagement. By raising awareness, providing accessible information, and promoting the benefits of sustainable waste management practices, individuals and communities can make informed choices and contribute to a cleaner and healthier environment.

1.4 Problems Encountered in Waste Handling

Technological bottlenecks in waste handling refer to challenges or limitations in the application of technology to effectively manage and process waste. These bottlenecks can arise at various stages of waste handling, from collection and sorting to treatment and disposal, which are shown in Figure 1.7.

Figure 1.7 Common technological challenges associated with waste handling. Adapted from [41].



Kumar and Agrawal et al. [41] reported that municipalities face problems in MSWM related to collection efficiency, treatment, and other factors. Inefficient collection systems, stemming from outdated routes or inadequate scheduling, can lead to missed pickups, uneven service distribution, and higher costs. Furthermore, limited integration of technology, such as GPS tracking or route optimization software, can hinder the optimization of collection routes and real-time monitoring.

Manual sorting at recycling facilities is labor-intensive and time-consuming, resulting in inefficiencies and inconsistencies in material recovery. Automated sorting technologies (optical sorters, magnetic separators) struggle to accurately identify and separate mixed or contaminated waste streams. Regarding quality control and contamination, it is estimated that contamination of recyclables with non-recyclables or hazardous substances lowers the quality and value of recovered materials [42, 43]. Existing technologies for contamination detection and quality control may have limited ability to effectively identify and remove contaminants. Processing capacity and efficiency also impact MSWM; limited processing capacity and outdated equipment in waste treatment facilities can create bottlenecks in waste-processing and disposal. Similarly, technological constraints, such as inefficient energy recovery systems or inadequate throughput, can impede the efficient conversion of waste into energy, compost, or recyclables.

Moreover, resource recovery and recycling are the crucial parts of MSWM, yet these are also responsible for waste disposal management such as technological limitations in recycling processes, such as the inability to effectively recycle certain types of plastics or composite materials, can restrict the recovery of valuable resources from waste streams, and lack of investment in research and development of innovative recycling technologies may impede progress toward achieving higher recycling rates and closing material loops [44]. In terms of data management and analytics, the limited use of data-driven technologies in waste management can hinder decision-making, resource allocation, and performance monitoring. Challenges in collecting,

integrating, and analyzing data across different waste management systems and stakeholders can impede efforts to optimize waste handling. Additionally, infrastructure development plays a key role; insufficient investment in facilities for waste handling (recycling centers, composting plants, WtE facilities) can limit the adoption and scalability of advanced technologies. Technological bottlenecks may arise from delays or setbacks in planning, permitting, and constructing new infrastructure projects. Thus, addressing technological bottlenecks in waste handling requires investment in research, development, deployment of advanced technologies, capacity building, and collaboration among stakeholders. Overcoming these challenges can improve the efficiency, sustainability, and resilience of waste management systems.

1.5 Economic Competitiveness

Waste is a byproduct of economic actions and related to it by government, household as well as suggested by Balasubramanian et al. [45] and further pointed out that in terms of energy recovery/material, waste is also an input to economic activity. Economic competitiveness in waste management refers to the ability of waste management systems, technologies, and practices to deliver cost-effective solutions while meeting environmental and regulatory requirements. Several factors contribute to the economic competitiveness of waste management, which are given in Table 1.4:

Table 1.4 Factors contributing to economic competitiveness of waste management. Adapted from [45].

Cost efficiency	Resource recovery	Energy generation	Market demand for recyclables
<ul style="list-style-type: none"> Waste management operations must be cost-efficient to remain competitive This includes factors such as collection, transportation, processing, and disposal costs Investments in technologies and infrastructure that improve operational efficiency can help reduce costs over the long term 	<ul style="list-style-type: none"> Waste management systems that prioritize resource recovery and recycling can enhance economic competitiveness by capturing the value of materials that can be reused or repurposed Recycling and recovery facilities can generate revenue from the sale of recovered materials, offsetting some of the costs associated with waste management 	<ul style="list-style-type: none"> Waste-to-energy technologies, such as incineration or anaerobic digestion, can contribute to economic competitiveness by generating electricity, heat, or biogas from waste materials Revenue generated from the sale of energy can offset operational costs and provide additional income streams 	<ul style="list-style-type: none"> Economic competitiveness in waste management is influenced by market demand for recyclable materials Fluctuations in commodity prices can impact the profitability of recycling operations Diversification of markets and development of domestic recycling infrastructure can help mitigate market volatility

Blagoeva et al. [46] suggested that waste management contributes to economic growth and development through innovation and technology. Investments in innovation and technology can drive economic competitiveness by improving sorting and processing technologies, automation, and data analytics, thereby enhancing efficiency, reducing operational costs, and improving the quality of recovered materials. Compliance with environmental regulations and waste management standards is essential for economic competitiveness. Non-compliance penalties can lead to additional costs and damage reputation. Proactive measures to meet or exceed regulations can help minimize risks and ensure long-term viability.

Moreover, transitioning to a circular economy, where materials are reused, recycled, and regenerated, can boost economic competitiveness in waste management. Circular economy principles promote resource efficiency, reduce waste generation, and create opportunities for innovation and value creation throughout the supply chain. Collaboration between public and private sectors can enhance economic competitiveness by combining resources, expertise, and innovation. Public-private partnerships can facilitate infrastructure investment, technology deployment, and service delivery, leading to cost savings and better outcomes. Thus, by prioritizing cost-effectiveness, resource recovery, innovation, and collaboration, waste management systems can improve economic competitiveness while advancing environmental sustainability and meeting societal needs.

1.6 Sustainable Challenges

Sustainable challenges in waste management systems encompass a range of issues related to environmental, social, and economic sustainability. These challenges vary depending on factors such as geography, population density, waste composition, and available resources. Common sustainable challenges as adumbrated by Srivastava et al. [47] in waste management are:

- 1. Waste Generation and Composition:** Rapid population growth, urbanization, and industrialization contribute to increased waste generation and changing waste composition, posing challenges for waste management systems. The proliferation of single-use plastics and packaging materials exacerbates waste management challenges due to their persistence in the environment and difficulties in recycling.
- 2. Waste Minimization and Prevention:** Promoting waste minimization and prevention strategies, such as source reduction, reuse, and repair, is essential for sustainable waste management. Encouraging behavioral changes and consumer awareness to reduce consumption, adopt eco-friendly alternatives, and embrace a circular economy mindset can help mitigate waste generation.
- 3. Resource Recovery and Recycling:** Maximizing resource recovery and recycling rates is critical for sustainable waste management. However, challenges such as contamination of recyclable materials, limited markets for recycled products, and inefficient recycling infrastructure hinder progress. Investment in recycling technology, market development, and public education is needed

to improve recycling rates and ensure the economic viability of recycling programs.

- 4. Waste Collection and Transportation:** Inefficient waste collection and transportation systems lead to increased energy consumption, GHG emissions, and operational costs. Optimizing collection routes, investing in alternative fuel vehicles, and implementing smart technologies for real-time monitoring and route optimization can improve the efficiency and sustainability of waste collection and transportation.
- 5. Waste Treatment and Disposal:** Sustainable waste treatment and disposal methods are essential to minimize environmental pollution, conserve natural resources, and protect public health. Challenges include limited capacity and outdated infrastructure for waste treatment, inadequate regulatory enforcement, and concerns about the environmental and social impacts of incineration and landfilling. Investing in advanced WtE technologies, composting facilities, and hazardous waste treatment plants can help address these challenges and promote sustainable waste management practices.
- 6. Community Engagement and Participation:** Engaging communities in waste management initiatives and fostering stakeholder participation is crucial for sustainable waste management. Lack of awareness, cultural attitudes, and socio-economic disparities can hinder community participation and support for waste reduction and recycling programs. Implementing education campaigns, outreach activities, and incentive programs to promote behavior change and community involvement can enhance the sustainability of waste management efforts.
- 7. Policy and Governance:** Strong policy frameworks and effective governance structures are essential for promoting sustainable waste management practices. Challenges include inadequate regulation and enforcement, lack of coordination among government agencies and stakeholders, and insufficient funding for waste management initiatives. Strengthening waste management policies, enhancing regulatory compliance, and fostering multi-stakeholder partnerships are key strategies for addressing these challenges and advancing sustainable waste management [48].

Addressing sustainable challenges in waste management requires a holistic approach that integrates environmental, social, and economic considerations. By adopting innovative technologies, engaging stakeholders, promoting waste reduction and recycling, and strengthening policy and governance frameworks, communities can build more resilient and sustainable waste management systems.

1.6.1 Feedstock Availability

Feedstock availability is a crucial consideration in waste management techniques, particularly in processes that involve the conversion of waste materials into valuable products or energy. The availability and composition of feedstock can vary depending on factors such as waste generation rates, waste streams, and regional characteristics [49]. Here's how feedstock availability influences various waste management techniques:

1. Waste-to-energy: WtE technologies, such as incineration and gasification, rely on the combustion or thermal conversion of waste materials to generate heat or electricity. Feedstock availability is critical for maintaining consistent energy output and operational efficiency in WtE facilities. The right investment in institutional and technological changes contributing in conversion of waste into sources that take part in socio-economic development [50]. MSW, biomass, and certain industrial wastes can serve as feedstock for WtE processes, but the composition and calorific value of the feedstock may vary, affecting process performance. Jamilatun et al. [51] proposed that composition, characteristics, and amount of waste differ in every country based on growth rate of population, income, and urbanization, and variety of alternative treatments can be carried out depending upon the waste composition such as paper, wood, plastics, cloth, etc., and transformed into energy via WtE technology as shown in Figure 1.8.

Thus, feedstock availability in the form of waste is an important part of WtE technologies, and in the same manner, these technologies even require consideration of financial, environmental aspects and energy efficiency.

2. Anaerobic Digestion: This is a biological process that converts organic waste into biogas (primarily CH_4) and digestate through microbial activity in the absence of oxygen. Feedstock for AD includes organic waste streams such as food waste, agricultural residues, sewage sludge, and animal manure. The availability and quality of organic feedstock influence biogas production rates, CH_4 content, and nutrient content in the digestate. Haque et al. [52] indicated that AD is a widely used technology for converting organic waste into valuable products due to its cost-effectiveness and applicability. However, its success depends on operating conditions and feedstock properties, which affect the quantity and quality of biogas and digestate produced. Supplementary processes like pyrolysis, hydrothermal liquefaction, and pretreatment methods can enhance biogas

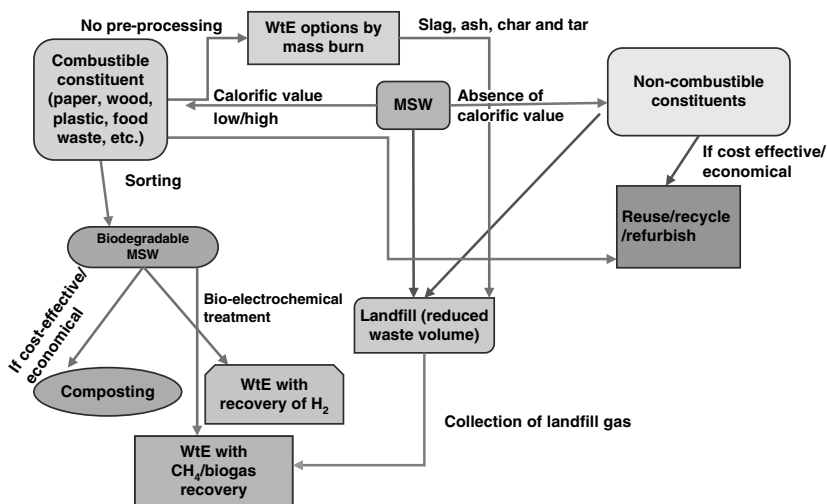


Figure 1.8 Technologies of waste treatment. Adapted from [52].

production and yield valuable byproducts, although challenges related to high operating temperatures and feedstock composition remain. Furthermore, understanding the composition and generation rate of MSW feedstock characteristics is necessary for designing full-scale biodigesters for municipal use and assessing environmental impact [53].

- 3. Composting:** Composting is a biological process where organic waste decomposes into nutrient-rich compost through microbial activity. Feedstock for composting includes organic materials like food scraps, yard waste, paper products, and agricultural residues. A proper balance of carbon (C) and nitrogen (N) ratios, moisture content, and particle size in the feedstock is essential for efficient composting and high-quality compost production. Cao et al. [54] proposed that feedstock characteristics (seasonality, maturation regimes) and processing technologies are key factors that improve the composition of MSW compost and the production of good-quality compost by influencing feedstock selection/screening. Additionally, industrialization and urbanization lead to complex MSW composition with more diverse feedstock and larger logistical networks, further contributing to the variety of compost properties.
- 4. Recycling:** Recycling processes involve collecting, sorting, and processing recyclable materials into raw materials or products for reuse. Feedstock for recycling includes materials like paper, plastics, glass, metals, and e-waste [42–55]. The availability of high-quality recyclable feedstock relies on effective waste collection and sorting systems, as well as consumer participation and material recovery rates [56].
- 5. Biofuels Production:** Biofuels, such as biodiesel and ethanol, can be produced from organic feedstock like vegetable oils, animal fats, crop residues, and dedicated energy crops. Feedstock availability, composition, and logistics are crucial factors in biofuel production, influencing the process's economics and sustainability. Skaggs et al. [57] emphasized the importance of feedstock in biofuel production, as biofuels are recognized as sustainable renewable energy that can replace fossil fuels and offer environmental benefits. Biofuels are classified into different generations based on feedstock characteristics, and these feedstocks are considered readily available and accessible, contributing to socio-economic growth. Utilizing waste feedstocks helps mitigate controversies related to using food materials for biofuels. Waste materials (including animal manures) contain various types of feedstocks that can be converted into diverse biofuels. Sharma et al. [58] suggested that organic waste (waste feedstock) is an efficient feedstock for biofuel production, offering opportunities across various manufacturing processes and potential for biofuels. Organic waste (food waste, farming waste, paper, corporate garbage, forestry, etc.) is inexpensive and readily available, thereby boosting the economic potential of biofuels and reducing pollution [23, 59].
- 6. Advanced Recycling Technologies:** Advanced recycling technologies, such as pyrolysis and chemical recycling, convert plastic waste into valuable products or feedstock for producing new plastics, chemicals, or fuels. Feedstock availability, feedstock quality, and feedstock consistency are key considerations in developing and scaling up advanced recycling processes [60].

In summary, feedstock availability plays a critical role in determining the feasibility, efficiency, and sustainability of various waste management techniques. Ensuring a reliable and consistent supply of suitable feedstock is essential for optimizing process performance and maximizing resource recovery from waste streams. Effective waste management strategies should consider feedstock availability as a fundamental aspect of planning, design, and implementation.

1.6.2 Operational Challenges

Operational challenges in waste management can arise at various stages of the waste management process, from collection and transportation to treatment and disposal. These challenges can impact efficiency, cost-effectiveness, and environmental performance. Some common operational challenges in waste management as suggested by Kwakye et al. [61] are given in Table 1.5:

Table 1.5 Challenges associated with waste management. Adapted from [61].

Common operational challenges	
Inefficient waste collection	<ul style="list-style-type: none"> • Poor route planning and scheduling can lead to inefficient collection, resulting in missed pickups, uneven service coverage, and higher operational costs • Inconsistent collection frequencies and service levels may cause overflowing bins, illegal dumping, and community dissatisfaction
Contamination of waste streams	<ul style="list-style-type: none"> • Contamination of waste streams with non-recyclable materials, hazardous substances, or inappropriate waste items can compromise the quality of recyclable materials and increase processing costs • Lack of public awareness, improper sorting practices, and inadequate enforcement of recycling guidelines contribute to contamination challenges
Limited access to collection services	<ul style="list-style-type: none"> • Rural and remote areas may face challenges in accessing waste collection services due to logistical constraints, long distances, and dispersed populations • Providing equitable access to collection services for underserved communities while addressing cost and operational barriers presents a challenge for waste management providers
Technological constraints	<ul style="list-style-type: none"> • Outdated or inadequate waste management infrastructure and equipment can hinder operational efficiency and performance • Limited use of technology, such as GPS tracking, route optimization software, and smart sensors, may impede real-time monitoring, data analysis, and decision-making in waste management operations
Waste transportation challenges	<ul style="list-style-type: none"> • Inefficient waste transportation systems, including outdated fleets, congested roadways, and long travel distances, can increase fuel consumption, emissions, and operational costs • Addressing logistical challenges, optimizing transportation routes, and reducing vehicle idle times are key strategies to improve the efficiency and sustainability of waste transportation

(Continued)

Table 1.5 (Continued)

Common operational challenges	
Capacity constraints in waste treatment facilities	<ul style="list-style-type: none"> Limited capacity in waste treatment facilities, such as landfills, incinerators, and recycling plants, can lead to bottlenecks in waste-processing and disposal Balancing waste generation rates with treatment capacity, implementing diversion strategies, and investing in infrastructure upgrades are necessary to address capacity constraints
Regulatory compliance and permitting	<ul style="list-style-type: none"> Compliance with environmental regulations, permitting requirements, and operational standards presents challenges for waste management operators Navigating complex regulatory frameworks, obtaining permits, and maintaining compliance with evolving regulations require dedicated resources and expertise
Financial sustainability	<ul style="list-style-type: none"> Funding constraints, revenue fluctuations, and budgetary pressures pose challenges for achieving financial sustainability in waste management Balancing service affordability with revenue generation, optimizing cost structures, and exploring alternative funding mechanisms are critical for ensuring long-term financial viability

Addressing operational challenges in waste management requires a comprehensive approach that integrates technology, infrastructure development, regulatory compliance, community engagement, and financial planning. Collaboration among stakeholders, innovation, and continuous improvement are essential for overcoming these challenges and advancing sustainable waste management practices.

1.7 Carbon Sequestration for Green and Sustainable Environment

Carbon sequestration in WtE processes involves capturing and storing carbon dioxide (CO₂) emissions generated during the combustion or thermal conversion of waste. While WtE technologies generate energy, they also release CO₂ and other GHGs, contributing to climate change [62]. Carbon sequestration aims to mitigate these emissions by capturing CO₂ and preventing its release into the atmosphere [63]. Carbon sequestration can be incorporated into WtE processes as follows:

- **Carbon Capture and Storage (CCS):** CCS technologies are specifically designed to intercept CO₂ emissions generated at WtE facilities before they are vented into the atmosphere. Post-combustion capture represents one primary approach, focusing on separating CO₂ from the flue gases downstream of the combustion process, often employing techniques such as absorption or adsorption. Alternatively, pre-combustion capture can be integrated with processes like waste gasification or pyrolysis, where waste is converted into a synthesis gas (syngas), and the CO₂ is removed from this syngas prior to its combustion.

Table 1.6 Processing conditions of CCS Technology. Adapted from [64].

Technology of CCS	Pressure (bar)	Processing temperature (K)	Concentration of CO ₂ (%)
Direct air capture	1.0	298	~0.05
Pre-combustion	14.0–70.0	473–723	16–61
Oxy-combustion	1.0	218	17–71
Post-combustion	1.0	313–333	4–21

The captured CO₂ is then typically transported and permanently stored in secure geological formations, such as depleted oil and gas reservoirs or deep saline aquifers, effectively preventing its re-entry into the carbon cycle. Table 1.6 provides an overview of typical operating conditions associated with various CCS technologies [64]. Table 1.6 summarizes the operating conditions of CCS technology.

- Carbon Capture and Utilization:** In parallel with storage, Carbon Capture and Utilization (CCU) technologies offer an avenue to convert captured CO₂ into commercially valuable products or industrial feedstocks. This approach provides an economic incentive that can support the implementation of carbon capture systems. One significant application of captured CO₂ is in mineralization processes, where it is reacted with minerals to form stable, long-term carbonate compounds. Beyond mineralization, captured CO₂ can also be leveraged in various other applications, including the synthesis of fuels, production of chemicals, polymerization processes, and manufacturing of building materials, effectively integrating waste-derived carbon into new product value chains.
- Bioenergy with Carbon Capture and Storage (BECCS):** BECCS represents a synergistic approach that couples the generation of energy from biomass with carbon capture and geological storage. This method utilizes biomass feedstocks, which can include organic waste, agricultural residues, or dedicated energy crops. A key advantage of using biomass is that it absorbs CO₂ from the atmosphere during its growth phase. When this biomass is subsequently converted into energy and the resulting CO₂ emissions are captured and stored, the overall process can potentially achieve net negative CO₂ emissions, meaning more CO₂ is removed from the atmosphere than is released. Consequently, BECCS holds significant potential to offset CO₂ emissions generated not only by WtE processes but also from other sources, thereby contributing substantially to climate change mitigation efforts.
- Enhanced Landfill CH₄ Capture:** Landfills constitute a notable source of CH₄ emissions, which is a potent GHG significantly contributing to climate change. This CH₄ is primarily produced through the anaerobic decomposition of organic waste materials buried within landfill sites. Enhanced LFG capture systems are specifically designed to collect these CH₄ emissions effectively. These systems can be readily coupled with WtE facilities, enabling the captured CH₄ to be utilized for energy production. By capturing and converting this potent GHG into usable energy, enhanced landfill CH₄ capture plays a

vital role in reducing overall GHG emissions and advancing climate change mitigation.

- **Carbon Offsetting and Carbon Credits:** Market-based mechanisms, such as carbon offsetting and carbon credits, provide financial frameworks to support emission reduction initiatives. WtE facilities that successfully implement carbon sequestration technologies may be eligible to generate carbon offset credits or participate in carbon trading schemes. These credits offer a financial incentive that can enhance the economic feasibility of emission reduction projects. Carbon offsetting, facilitated by these credits, allows organizations to compensate for their unavoidable emissions by investing in projects elsewhere that reduce or sequester an equivalent amount of CO₂, such as those implemented at WtE facilities equipped with CCS capabilities.

Integrating carbon sequestration technologies into WtE processes can help mitigate GHG emissions, reduce the carbon footprint of waste management systems, and contribute to climate change mitigation efforts. However, challenges related to technological feasibility, cost-effectiveness, and regulatory requirements must be addressed to fully realize the potential of carbon sequestration in WtE operations.

1.8 IoT Services

According to Tamakloe et al. [65], the integration of IoT technologies in WtE techniques offers several benefits, including improved efficiency, real-time monitoring and data-driven decision-making, and proposed smart waste management design as shown in Figure 1.9.

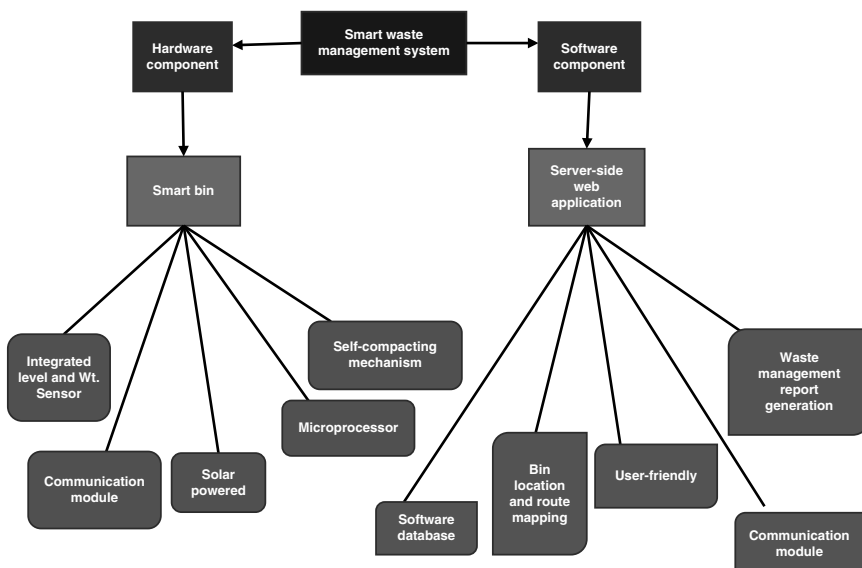


Figure 1.9 Design component structure of waste management. Adapted from [65].

As shown in Figure 1.9, the hardware design implementation involves efficient coordination of sensors and microprocessors for effective system function. The software design utilizes a developed web application based on the Adonis JS web framework, representing a modern waste management system. As recommended by Khan et al. [66], the integration of IoT technologies within waste management significantly enhances operational efficiency across collection, routing, and equipment monitoring. At the level of individual bins, IoT sensors provide real-time data on fill levels, temperature, and other parameters. This sensor data is leveraged to dynamically optimize waste collection routes and schedule pickups precisely according to necessity, thereby preventing both overflowing bins in dense areas and inefficient trips to underutilized containers. Extending this capability to transportation, IoT-enabled fleet management systems offer real-time tracking of waste collection vehicles, monitoring their location, operational status, and performance. By synthesizing data from bins, vehicles, and traffic conditions, sophisticated route optimization algorithms can be applied to enhance logistical efficiency, resulting in reduced fuel consumption and minimized associated emissions. Furthermore, IoT facilitates the remote monitoring of waste-processing equipment and facilities, including incinerators, gasifiers, and digesters. Sensors placed on these assets continuously monitor operational parameters and performance metrics, providing essential data for performance assessment and proactive maintenance planning. This remote oversight enables prompt detection of equipment anomalies, identification of inefficiencies, and scheduling of preventive repairs, thereby minimizing unplanned downtime and optimizing facility throughput.

Beyond direct operational improvements, IoT applications contribute significantly to energy management, environmental oversight, and predictive capabilities within waste management systems. IoT-based energy management systems offer comprehensive monitoring of energy consumption, generation, and distribution at WtE facilities. Utilizing smart meters and sensors, these systems enable the optimization of energy usage, allow for adaptive production adjustments based on demand, and pinpoint opportunities for efficiency enhancements. Environmental monitoring and regulatory compliance are also bolstered by IoT integration. Sensors measure key parameters such as air quality, GHG emissions, and other environmental indicators. Continuous Emissions Monitoring Systems (CEMSs), often IoT-enabled, track pollutant levels, detect non-compliance anomalies, and trigger alerts for necessary corrective actions. Operational data, including historical trends, is analyzed using IoT data analytics platforms to identify performance patterns and predict potential equipment failures, enabling a shift toward predictive maintenance strategies. These algorithms prioritize maintenance tasks and schedule interventions proactively, further reducing unscheduled downtime. Finally, IoT-enabled WtE systems can integrate with smart grids and energy markets. This connectivity allows for the optimization of energy production, storage, and distribution in response to real-time grid conditions, market prices, and renewable energy availability, contributing to grid stability and potentially increasing revenue streams.

By leveraging IoT services, WtE techniques can achieve greater efficiency, reliability, and sustainability while reducing operational costs and environmental

impact. However, challenges such as data security, interoperability, and scalability need to be addressed to realize the full potential of IoT in WtE applications.

1.9 Smart City Infrastructure

WtE plays a significant role in smart city infrastructure by contributing to sustainability, resilience, and resource efficiency [67]. WtE technologies occupy a significant and multifaceted role within the development of smart urban infrastructure, contributing fundamentally to sustainability, resilience, and overall resource efficiency [60]. A primary contribution lies in energy production and security; WtE facilities convert organic waste into various energy carriers – electricity, heat, or biofuels – decreasing reliance on fossil fuels and enhancing energy independence. Furthermore, their capacity for distributed energy generation and integration with smart grids allows for optimized production, distribution, and consumption, bolstering the reliability and efficiency of the urban energy network and contributing to grid stability by balancing supply and demand. Beyond energy, WtE drives significant advancements in waste management optimization. Providing a vital alternative to traditional landfilling and open burning, these technologies minimize environmental impacts and substantially reduce landfill CH₄ emissions. This aligns with circular economy principles, as WtE facilities facilitate resource recovery by extracting energy and valuable materials such as metals, organic matter, and plastics from waste streams. When integrated with smart waste management systems, WtE enables real-time monitoring, optimized collection routes, and more efficient utilization of waste resources, supporting conservation efforts within the smart city framework. The environmental and public health benefits are also profound; by treating waste that would otherwise decompose and release CH₄ or be combusted inefficiently, WtE processes contribute directly to climate change mitigation by reducing GHG emissions, with advanced techniques like carbon capture and utilization/storage (CCUS) potentially amplifying these benefits. Moreover, modern WtE facilities employ sophisticated pollution control technologies that significantly minimize emissions of air pollutants, particulate matter, and hazardous substances, leading to improved air quality and contributing positively to public health and overall environmental sustainability within urban areas. The implementation of smart WtE systems fosters data-driven decision-making by leveraging sensors, advanced data analytics, and predictive algorithms to optimize operational performance, maintenance scheduling, and energy efficiency, providing necessary insights for proactive management. Finally, successful WtE initiatives actively promote community engagement and public education, raising awareness about waste management, energy recovery, and sustainability, which cultivates a sense of shared ownership and responsibility essential for achieving sustainable development goals in future smart cities.

By leveraging WtE technologies and integrating them with smart city infrastructure, urban areas can achieve greater sustainability, resilience, and livability while addressing challenges related to waste management, energy security, and climate change mitigation.

1.10 Conclusion and Discussion

In conclusion, integrating WtE technologies into smart city infrastructure offers significant benefits across multiple dimensions of sustainability, resilience, and resource efficiency. By converting organic waste into electricity, heat, or biofuels, WtE facilities contribute to energy security, reduce GHG emissions, and promote the transition to a circular economy. Furthermore, WtE plays a key role in optimizing waste management processes, enhancing resource recovery, and mitigating environmental pollution in urban areas. The synergy between WtE and smart technology initiatives facilitates data-driven decision-making, real-time monitoring, and optimization of energy production, waste collection, and grid integration. By harnessing IoT technologies, advanced analytics, and smart grid capabilities, WtE systems improve operational efficiency, reduce environmental impacts, and encourage community engagement in sustainable waste management practices. Overall, the integration of WtE represents a holistic approach to urban sustainability, tackling interconnected challenges in waste management, energy production, climate change mitigation, and public health. Through cooperation among government bodies, private sector stakeholders, and local communities, cities can utilize WtE technologies to build more resilient, livable, and sustainable urban environments for present and future generations.

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