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Municipal Solid Waste Management in Erbil City: Challenges, Solutions, and Future Prospects

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Dedication

Acknowledgement

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Abstract

This study examines the current state of municipal solid waste (MSW) management in Erbil City, identifying key challenges and proposing sustainable strategies aligned with international best practices. Findings reveal a growing waste stream dominated by organic and non-recyclable materials, inadequate infrastructure, poor regulatory enforcement, and low public awareness. The city relies heavily on open dumping at Kani Qirzhala, which lacks essential environmental safeguards. Through comparative analysis of successful models in cities such as Pune and Baku, the research highlights the importance of integrated policy frameworks, public-private partnerships, source separation, and investment in engineered disposal and recycling infrastructure. Recommendations include the introduction of a comprehensive waste management by-law, expansion of collection and sorting systems, development of composting and material recovery facilities, and modernization of landfill operations. The study concludes by outlining future research directions in waste characterization, socio-economic feasibility, and digital citizen engagement, offering a roadmap for transitioning Erbil toward a circular and resilient MSW system.

Keywords: Municipal Solid Waste (MSW), Erbil City, Waste Management, Circular Economy, Environmental Policy, Waste-to-Energy

Chapter One: Introduction

1.1 Background and Importance of MSW Management

Municipal Solid Waste (MSW) management constitutes a critical urban service, encompassing the systematic control of waste activities from generation through to final disposal, including storage, collection, transportation, processing (sorting, treatment), and resource recovery (recycling, energy generation). This complex, multi-level process involves intricate coordination between governmental policies, legal frameworks, financial resources, administrative structures, and research efforts (Zhang et al., 2021). It primarily addresses waste generated from residential, commercial, and institutional sources, distinct from industrial or hazardous waste streams. The core components – collection, transportation, processing, recycling, and disposal – function as an interconnected system; failures in early stages, such as inadequate collection which persists notably in developing regions, inevitably compromise the effectiveness of subsequent treatment, recovery, or safe disposal efforts, leading to cascading negative consequences (Adedara et al., 2023). Historically, waste management practices evolved reactively alongside urbanization. While rudimentary methods like dumping waste outside city limits existed in antiquity, significant shifts were primarily driven by public health crises and mounting environmental concerns, particularly gaining political traction in developed nations from the 1970s onwards (Abubakr et al., 2022). Key drivers for modern MSWM include not only public health and environmental protection but also resource scarcity awareness, climate change mitigation, and technological advancements. Compounding the challenge is the dramatic increase in global waste generation, fueled by population growth, economic development, and escalating consumption patterns, projected to surge from approximately 2 billion tons in 2016 to 3.4 billion tons by 2050, with developing nations facing the steepest increases and often lagging in infrastructure development (Maalouf and Agamuthu, 2023).

The importance of effective MSW management is profoundly underscored by its direct impact on public health. Inadequate practices create substantial risks, potentially leading to the collapse of essential sanitation services and exacerbating health crises, as observed during pandemics (Vinti e al., 2021). Uncollected waste and open dumpsites serve as fertile breeding grounds for disease vectors like insects and rodents, facilitating the transmission of malaria, dengue fever, cholera, typhoid, and various diarrheal diseases. Leachate, the toxic liquid percolating through decomposing waste in improperly managed landfills and dumpsites, poses a severe threat by contaminating soil, surface water, and groundwater sources used for drinking and agriculture. This contamination introduces pathogens, heavy metals, and persistent organic pollutants into the environment, leading to waterborne illnesses and potential long-term health effects, including cancer. Furthermore, air quality is significantly degraded through practices like open burning, which releases harmful particulate matter, dioxins, and furans, contributing to respiratory diseases such as asthma and bronchitis. Landfills also emit methane (a potent greenhouse gas) and other noxious gases like hydrogen sulfide and ammonia, impacting local air quality, contributing to climate change, and causing respiratory irritation (Gebrekidan et al., 2024). Epidemiological studies confirm these risks, associating residency near MSW facilities, particularly older or poorly managed ones, with increased incidences of adverse birth outcomes, respiratory conditions, and negative mental health effects. Critically, the burden of these health impacts often falls disproportionately on marginalized and low-income communities who frequently experience lower service coverage and live in closer proximity to disposal sites, highlighting a significant environmental justice dimension to MSWM failures (Abubakr et al., 2022).

Environmentally, different MSW management methods present distinct impact profiles. Landfilling, while a prevalent disposal method, generates hazardous leachate that threatens water and soil quality and produces significant methane emissions during anaerobic decomposition, contributing substantially to global greenhouse gas levels (Siddiqua et al., 2022). Incineration drastically reduces waste volume and offers the potential for energy recovery. Modern waste-to-energy (WtE) facilities, when equipped with advanced pollution control technologies, can manage emissions; however, challenges related to air pollutants (including CO2, dioxins, and particulate matter) and the safe disposal of residual ash persist. Compared to landfilling, WtE can offer greenhouse gas benefits if the energy recovered displaces fossil fuel consumption. Recycling provides substantial environmental advantages by conserving natural resources, reducing the energy required for manufacturing virgin materials, and lowering overall greenhouse gas emissions compared to both landfilling and incineration (Luo et al., 2024). However, effective recycling necessitates robust collection, sorting infrastructure, and stable markets for recycled materials. Ultimately, linear waste management approaches centered on disposal lead to the depletion of valuable resources. The environmental performance of any method heavily depends on the technological sophistication, operational standards, and its integration within a comprehensive waste management strategy favoring waste reduction and recovery (Vaverková, 20219).

Modern MSWM is increasingly framed within the principles of resource conservation and the circular economy (CE), aiming to transition from a linear 'take-make-dispose' paradigm towards systems that maximize resource value and minimize waste. The waste hierarchy serves as the foundational guideline, prioritizing strategies in order of environmental preference: prevention, preparing for reuse, recycling, other recovery (including energy recovery), and lastly, disposal (Awino and Apitz, 2024). Material recovery through effective sorting and recycling is central to conserving virgin resources and reducing the environmental footprint of production. Energy recovery via WtE technologies provides a means to extract value from non-recyclable waste fractions, reducing landfill dependency and generating energy, potentially contributing to climate change mitigation. Despite the widespread adoption of CE principles in policy, a significant gap often exists between these ideals and implementation realities. High rates of landfilling and incineration persist globally, and achieving high levels of recycling and recovery demands substantial investment, technological adaptation, public participation, and systemic changes. Furthermore, inherent tensions can arise, such as the potential conflict between the need for consistent waste feedstock for large-scale WtE plants and the overarching CE goal of waste reduction (Savini, 2021).

The socio-economic dimensions further highlight the complexity of MSWM. Operational costs represent a significant financial burden for municipalities, particularly in developing countries where waste management competes with other essential services for limited funding. However, effective MSWM also generates considerable economic opportunities, including job creation in collection, sorting, recycling industries, WtE facility operation, and the manufacturing sector utilizing recovered materials. Recycling markets and energy sales from WtE can provide revenue streams. The informal sector often plays a vital, albeit frequently unrecognized and precarious, economic role in waste recovery, especially in the Global South (Lakiotia et al., 2017). Public perception and participation are indispensable for success; social acceptance, awareness, and active engagement in programs like source separation are crucial for operational efficiency and achieving policy goals, while opposition (e.g., NIMBYism) can impede facility development. Addressing environmental justice remains paramount, requiring policies that ensure equitable service provision, prevent the disproportionate siting of waste facilities in vulnerable communities, and promote the fair integration and protection of informal waste workers. Balancing these intricate socio-economic factors, cost, economic benefit, public acceptance, and equity is essential for designing and implementing MSWM systems that are not only environmentally sound but also socially just and economically sustainable. Effective MSW management, therefore, emerges as a fundamental pillar of sustainable urban development, inextricably linked to public health, environmental integrity, resource stewardship, and social equity across the globe (Maddi, 2024).

1.2 Current Global Trends in MSW Management

The management of Municipal Solid Waste (MSW) has become a critical global issue, intensified by rapid urbanization, population growth, and changing consumption patterns that are projected to increase annual global waste generation significantly by 2050 (Araújo et al., 2021; Kaza et al., 2018). In response, the global paradigm is shifting away from traditional linear "take-make-dispose" models towards more integrated, sustainable, and resource-oriented strategies. This evolution is driven by increasing awareness of environmental degradation (e.g., pollution, greenhouse gas emissions), public health risks, and the need for resource conservation associated with inadequate waste management (Araújo et al., 2021; Abubakar et al., 2022).

A foundational principle guiding modern waste management, particularly influential in European policy but gaining worldwide recognition, is the Waste Hierarchy (Gómez Palacios et al., 2002; Kituku et al., 2021). This hierarchy prioritizes waste management strategies in a preferred order: Prevention first, followed by Preparing for Reuse, Recycling, Other Recovery (including energy recovery), and finally, Disposal as the least desirable option (Ferrari et al., 2016; Directive 2008/98/EC cited in Ferrari et al., 2016 and Gharfalkar et al., 2015). The goal is to maximize resource efficiency and minimize environmental harm by moving waste management practices up the hierarchy (Ferrari et al., 2016). However, its application requires flexibility, acknowledging that socio-economic contexts and local deficiencies, especially in developing nations, might necessitate prioritizing foundational steps like improving collection and raising awareness initially (Ferrari et al., 2016; Price & Joseph, 2000). Some analyses also suggest considering socio-economic costs and benefits alongside environmental factors when applying the hierarchy (Vollebergh & Dijkgraaf cited in Environmental Assessment Institute, 2005).

Complementing the hierarchy, the Integrated Sustainable Waste Management (ISWM) framework provides a holistic approach, particularly relevant for developing countries (Wilson et al., 2012; Schübeler et al., 1996). ISWM integrates both the physical elements of waste management – Collection (driven by public health), Waste Treatment and Disposal (driven by environmental protection), and the 3Rs (Reduce, Reuse, Recycle, driven by resource recovery) – with crucial governance aspects (Wilson et al., 2012). These governance pillars include Inclusivity (engaging users, formal/informal service providers, government, NGOs), Financial Sustainability (ensuring long-term viability), and Sound Institutions and Proactive Policies (clear responsibilities, effective regulations, capacity building) (Wilson et al., 2012; Schübeler et al., 1996). This comprehensive focus distinguishes ISWM from the more technology-centric Integrated Waste Management (IWM) concepts often applied in developed nations (Wilson et al., 2012). Effective ISWM requires multi-stakeholder collaboration and addressing institutional weaknesses like coordination and funding, which are chronic challenges in many developing regions (Teshome et al., 2022; Naveen, 2021).

The concept of the Circular Economy (CE) is increasingly influencing waste management globally (Ghisellini et al., 2016; Khan et al., 2022). CE aims to decouple economic growth from resource consumption by designing out waste and viewing discarded materials as valuable resources (Aiguobarueghian et al., 2024). In waste management, CE promotes strategies aligned with the upper tiers of the waste hierarchy (reduce, reuse, recycle, recover) to create closed-loop systems. Adopting CE principles offers significant economic benefits, including stimulating innovation, creating new business models (e.g., product-as-a-service), generating employment, achieving cost savings through resource efficiency, and developing secondary markets for recovered materials (Aiguobarueghian et al., 2024; Hegab et al., 2023). However, transitioning to a CE requires overcoming policy, financial, and technological barriers, and fostering collaboration among businesses, policymakers, and institutions (Aiguobarueghian et al., 2024; Khan et al., 2022).

Technological advancements continue to offer new tools for MSW management. Waste-to-Energy (WtE) technologies, such as incineration with energy recovery, pyrolysis, and gasification, aim to reduce waste volume while generating energy (Palacio, 2019; Kumar & Samadder, 2017). Biological treatments like composting and anaerobic digestion (AD) are vital for managing the high organic fraction common in MSW globally, producing soil amendments and biogas, respectively (Teshome et al., 2022; Abubakar et al., 2022). Landfilling is evolving from uncontrolled dumping towards engineered sanitary landfills with environmental controls like liners and leachate/gas management systems. Furthermore, smart technologies, including the Internet of Things (IoT) and Artificial Intelligence (AI), are being increasingly integrated to optimize collection routes, improve sorting efficiency, monitor sites, and enhance overall system management (Espuny et al., 2021; Hegab et al., 2023). AI, for instance, shows potential in significantly reducing transport distances and costs while improving sorting accuracy.

Effective MSW management is underpinned by robust policy instruments and governance models. Trends include implementing Extended Producer Responsibility (EPR) schemes, Pay-As-You-Throw (PAYT) systems (Alzamora & Barros, 2020), landfill taxes or bans, recycling subsidies, and comprehensive public awareness campaigns (Abubakar et al., 2022; Teshome et al., 2022). Strong institutional coordination, clear responsibilities, financial sustainability (often requiring external financing beyond user fees), and inclusive, collaborative approaches involving government, the private sector (formal and informal), and civil society are recognized as essential for success (Wilson et al., 2012; Teshome et al., 2022; World Bank, 2018). The global trend points towards integrating these principles and technologies into tailored, locally appropriate systems to address the multifaceted challenge of sustainable MSW management.

1.3 Objectives of the Study

This research focuses on the case of Erbil City and is guided by several key objectives. The study is designed to explore and address the following objectives:

- To assess the current state of municipal solid waste management in Erbil City, including an evaluation of existing waste generation, collection, and disposal practices, and the identification of major challenges impacting the system.
- To investigate and propose potential solutions and strategies for improving MSW management in Erbil, drawing from global best practices and innovative approaches, in order to tackle the identified challenges and inefficiencies.
- To examine the future prospects for sustainable MSW management in Erbil City, including considerations of how emerging trends, policies, and technologies could be applied in the

local context, and to develop recommendations that align with long-term urban development plans and sustainability goals.

1.4 Scope and Methodology

The scope of the study is focused primarily on the municipal solid waste stream in Erbil City – that is, waste generated by households, businesses, and institutions that is managed by the municipal authorities. The study does not cover other waste types such as industrial, hazardous, or medical waste, except insofar as they might incidentally intersect with the municipal waste system. Geographically, the scope is limited to the administrative boundaries of Erbil City, the capital of the Kurdistan Region of Iraq. The time frame of analysis is contemporary (covering roughly the past decade up to the present), with an outlook toward future developments over the next several years. Within this scope, key aspects examined include waste generation rates and composition in Erbil, the existing collection and transportation infrastructure, methods of waste treatment and disposal in use, and the regulatory and institutional framework governing waste management in the city.

In terms of methodology, the research employs a case study approach to investigate Erbil's MSW management in depth. A case study methodology is well-suited for this topic as it allows for detailed, context-specific analysis of complex issues within a real-life setting. By treating Erbil as a case example, the study can integrate various data sources – including a review of academic literature, analysis of city records and reports, and, if available, stakeholder interviews or field observations – to build a comprehensive picture of the waste management situation. This qualitative, exploratory approach facilitates a holistic understanding of the interplay between technical, economic, and socio-cultural factors in Erbil's waste system. Moreover, the case study findings for Erbil are considered in light of global MSW management practices and challenges (as outlined in the background), enabling the research to draw comparisons and contrasts that enrich the analysis. The methodology thereby combines descriptive analysis of Erbil's current MSW management with an evaluative component, wherein proposed solutions and future scenarios are discussed based on evidence and best practices from the broader field. Ultimately, this approach provides both a diagnostic assessment of Erbil's MSW management and a set of contextually grounded recommendations, fulfilling the objectives of the study.

Chapter Two

Municipal Solid Waste Management: Global and Local

2.1 Definition and Classification of MSW

Municipal solid waste (MSW) generally refers to the stream of solid waste generated by everyday activities in urban areas and collected by municipalities. In practical terms, MSW encompasses household garbage and similar wastes from commercial, institutional, and municipal sources (Viriginia Law, 2011). The European Union defines municipal waste as "waste from households, as well as other waste which, because of its nature or composition, is similar to waste from households" (Lyeme et al., 2016). This definition highlights that MSW includes not only residential refuse but also waste from sources such as shops, offices, restaurants, schools, hospitals and other institutions, so long as it is similar in type to household waste. Industrial, medical, and construction waste are typically excluded or managed separately due to their specialized handling requirements.

1. **Classification by Source:** MSW can be classified by its source of generation. The primary sources are usually residential waste (household and domestic garbage), commercial waste (waste from businesses, markets, hotels, restaurants, etc.), and institutional waste (from schools, offices, government buildings, etc.). Some classifications also include municipal services waste, which covers street sweepings, park and landscape maintenance waste, and waste from municipal litter collections (Figure 2-1) (Viriginia Law, 2011). By defining MSW in terms of these source categories, waste management authorities can design collection and handling strategies appropriate for each stream (for example, household waste might be collected door-to-door, while commercial waste might require bulk collection services).

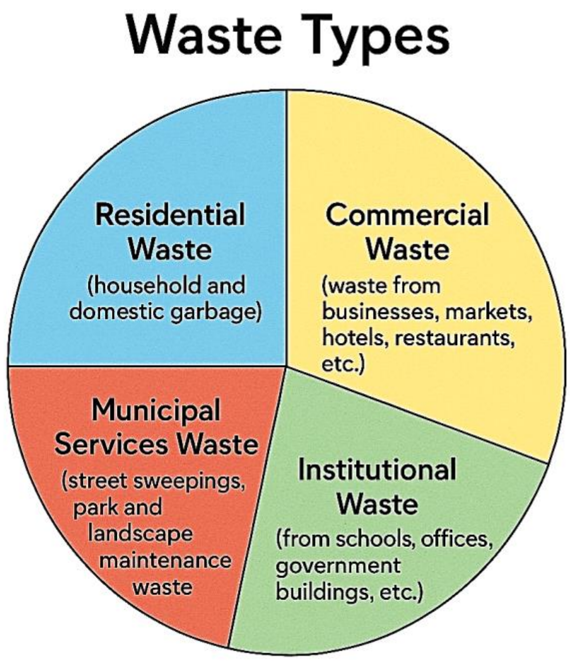

Figure 2-1: types of municipal wastes based on their origin.

2. **Classification by Composition:** Another way to classify MSW is by material composition or physical characteristics. Common categories include organic waste (biodegradable materials such as food scraps, yard trimmings and paper), recyclables (such as plastics, glass, metal, paper/cardboard that can be reprocessed), hazardous waste (household hazardous items like batteries, paints, medicines, which are a small part of MSW), and others (inert materials, composites, etc.)(Figure 2-2). In many cities, the organic fraction (food and green waste) forms a significant portion of MSW, with the remainder made up of varying amounts of paper, plastic, glass, metals, textiles, wood, leather, rubber, and other materials. For example, the U.S. Environmental Protection Agency notes that MSW includes everyday items like product packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, etc., originating from homes and institutions (EPA, 2016). These items can further be sorted into the categories above for analysis and management. Effective MSW management often depends on understanding this composition – for instance, a city with a high organic content in its waste might prioritize composting and biowaste collection, whereas a city with a high fraction of recyclables might focus on recycling programs.

In summary, MSW is defined by the scope of everyday urban solid waste under municipal responsibility, and it is classified either by where it comes from (residential, commercial, institutional, etc.) or by what it is made of (organics, plastics, paper, etc.). These definitions and classifications set the stage for analyzing waste generation trends and management practices on both global and local scales, as discussed in the following sections.

Figure 2-2: waste types based on composition.

2.2 MSW Generation Trends Worldwide

The generation of municipal solid waste has been increasing worldwide in line with population growth, urbanization, and economic development. Global MSW generation is currently on order of billions of tons per year and is projected to continue rising steeply in the coming decades. According to World Bank estimates, about 2.01 billion tons of MSW were generated worldwide in 2016, and this is expected to grow to 3.40 billion tons by 2050, a roughly 70% increase (World Bank, 2018). This growth rate outpaces global population growth, implying an increasing per capita waste generation over time. Indeed, global average waste generation is about 0.74 kilograms per person per day, but there is a very wide range across countries – from as low as 0.11 kg per person per day in some low-income settings to as high as 4.5 kg per person per day in high-income locales. The trend is that as countries develop economically, their per capita waste generation tends to increase up to a certain saturation point (World Bank, 2018).

Waste Generation and Income Levels: There is a strong positive correlation between waste generation rates and national income levels. Higher-income countries not only consume more goods (and hence produce more waste per person) but also tend to use more packaging and disposable items. As a result, high-income nations, while accounting for only about 16% of the world's population, generate an estimated 34% of the world's waste (approximately 683 million tons annually) (World Bank, 2018). In contrast, low-income countries (about 9% of global population) generate only around 5% of global MSW. In per capita terms, the average resident of a high-income country might produce around 1.5–2+ kg of MSW per day, whereas someone in a low-income country might produce only 0.5 kg or less per day. For example, North America (which includes the United States and Canada) has one of the highest regional per capita waste generation rates in the world – about 2.2 kg per person per day on average – whereas Sub-Saharan Africa's average is around 0.46 kg per person per day (Ellis, 2018). These disparities reflect differences in consumption patterns, lifestyles, and product use. However, as developing countries urbanize and incomes rise, per capita waste generation in those countries is increasing rapidly. World Bank projections indicate that by 2050, daily per capita waste generation could increase by 19% in high-income countries, but by 40% or more in low- and middle-income countries, as these nations industrialize and urbanize (World Bank, 2018).

Regional Trends: The burden of MSW generation is not evenly distributed across regions. Currently, the East Asia and Pacific region generates the largest share of the world's municipal waste (about 23% of the global total by weight), owing largely to the enormous populations and growing cities in countries like China. Europe and Central Asia, Latin America and the Caribbean, and South Asia each contribute significant portions (on the order of 14–20% each) of global waste (Figure 2-3). The Middle East and North Africa region produces the smallest share of global MSW (around 6%), partly due to smaller population size relative to other regions (World Bank, 2018). However, future growth in waste generation is expected to be most dramatic in today's lower-income regions. Sub-Saharan Africa, for instance, is forecast to triple its annual waste generation by 2050 if current trends hold, and South Asia's waste generation is projected to more than double by 2050 (World Bank, 2018). By mid-century, these two regions together could account for a much larger fraction of the world's waste, reflecting both population expansion and rising per capita waste generation (**Figure 2-4**) (World Bank, 2018).

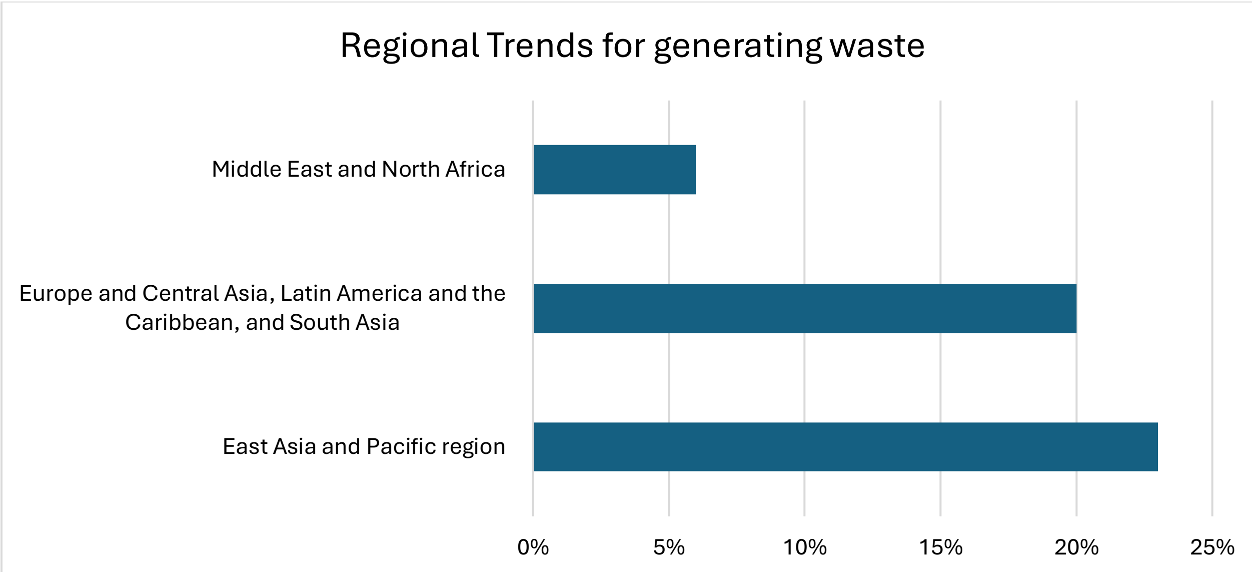

Figure 2-3: Share of waste generation for each region based on % world manucipal waste.

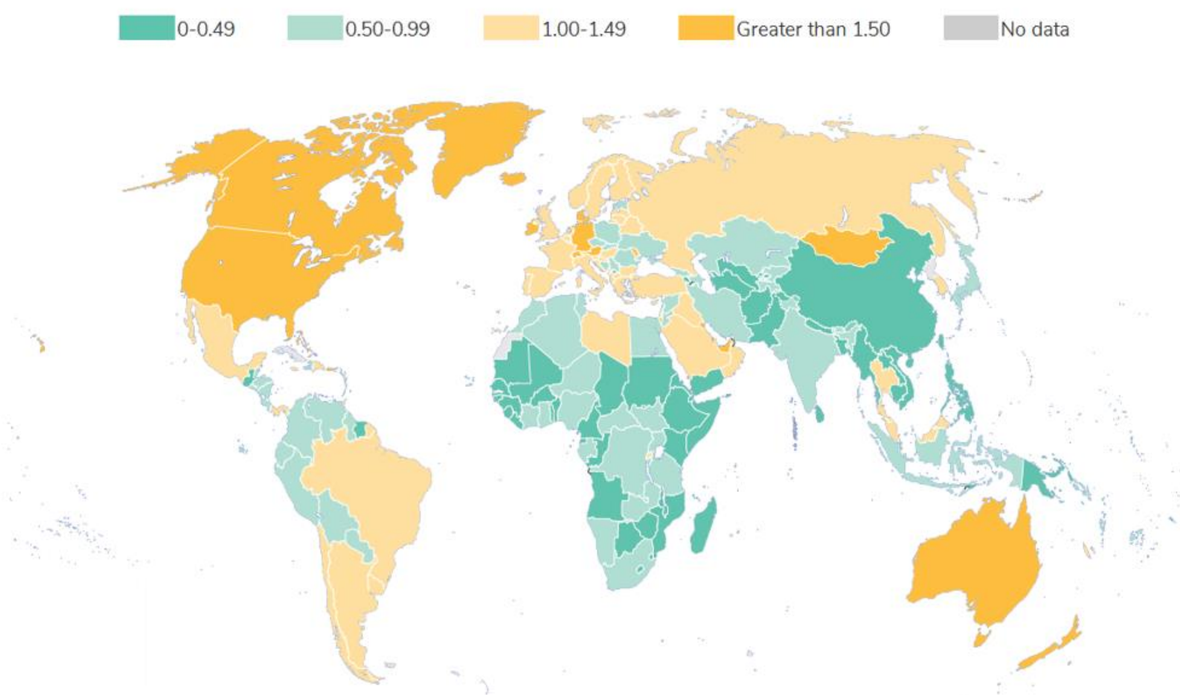

Figure 2-4 Global variation in municipal waste generation rates. This map illustrates MSW generation per capita across countries (kg per person per day). Higher-income countries (in orange) tend to produce over 1.5 kg/person/day, whereas many lower-income countries

Waste Management and Disposal Trends: An important aspect of global MSW trends is how the waste is managed after generation. Unfortunately, a significant portion of the world's waste is not managed in an environmentally safe manner. Globally, as of 2016, it was estimated that about

33% of MSW is openly dumped rather than properly disposed. Only about 19% of global MSW is recycled or composted, and about 11% is treated via modern incineration with energy recovery. The remaining portion (roughly 37%) is disposed of in sanitary landfills or otherwise controlled facilities (Figure 2-5) (Kaza et al., 2018). These averages mask huge differences between high- and low-income regions (elaborated in Section 2.4), but the overall picture is that one-third or more of the world's municipal waste ends up polluting the environment through open dumping or burning. The World Bank (2018) notes that at least 33% of global MSW is not managed in an environmentally safe way, and other studies have similarly found that a large share of waste, especially in developing countries, is dumped in unauthorized sites or burned in the open, contributing to health and environmental problems (Ellis et al., 2018). The growth in waste volumes, if not accompanied by improvements in waste management infrastructure, could exacerbate these issues. On a positive note, many cities and countries are recognizing the need for more sustainable waste management as part of their development trajectory – this includes investing in recycling programs, waste reduction initiatives, and improved collection and disposal. Nevertheless, without significant interventions, global waste generation trends pose serious challenges for sustainability, public health, and the environment.

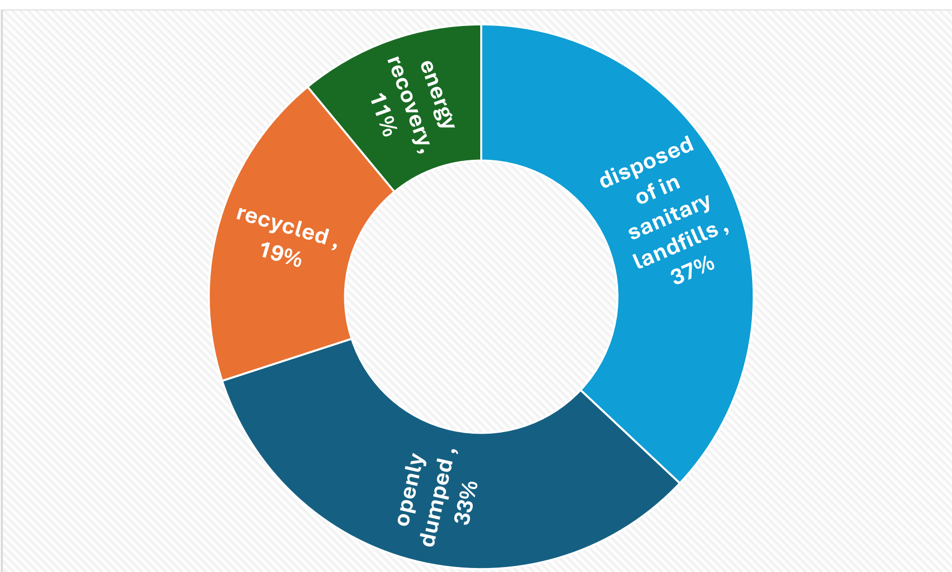

Figure 2-5: the share of different municipal management trend.

2.3 Composition of MSW in Different Economic Groups

The material composition of municipal solid waste varies greatly across countries and economic contexts. Key components of MSW include organic matter (food and yard waste), paper and cardboard, plastics, metals, glass, textiles, wood, and miscellaneous inorganic materials. The proportion of these components in the waste stream is influenced by factors such as income level, consumption patterns, and cultural habits. Generally, low-income countries' waste streams are dominated by organic material, while higher-income countries have a more diverse waste composition with higher fractions of paper, plastics, and other packaging materials (Kaza et al., 2018).

Globally, the single largest component of MSW is organic waste. Food scraps, yard trimmings, and other "food and green" waste account for about 44% of worldwide MSW on average. The next largest category collectively are the dry recyclables: paper/cardboard, plastic, glass, and metal together make up roughly 38% of global MSW. A World Bank analysis (Kaza et al., 2018) found that, by percentage of total waste mass, the global average composition was approximately: 44% organic waste, 17% paper and cardboard, 12% plastic, 5% metal, 4% glass, and the remaining share consisting of wood, rubber/leather, and other miscellaneous materials (Kaza et al., 2018). This indicates that nearly half of all municipal waste is biodegradable if properly managed, while a significant portion is potentially recyclable material.

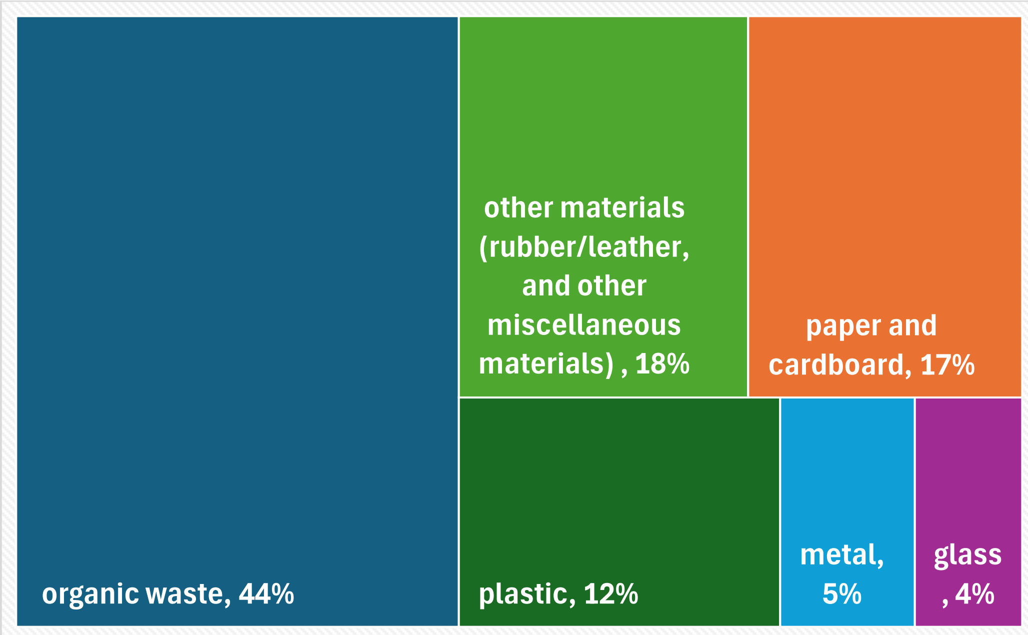

Figure 2-6: the global average composition of municipal solid waste (Kaza et al., 2018).

However, these global averages conceal stark **differences between economic groups**:

- **Low-Income Countries:** In lower-income economies, a very large fraction of MSW is organic. Foods, vegetable peels, agricultural residues and other biodegradable matter can often constitute 50–60% or more of the municipal waste by weight (Kaza et al., 2018). For example, waste audits in many low-income cities show over 55% organic content (mostly food waste). Meanwhile, the proportions of paper, plastics, and other packaging are relatively low. Plastics might make up only around 5–10% of MSW in low-income settings, and paper perhaps a similar small percentage (Kaza et al., 2018). The "other" category can also be significant in developing countries – this often includes dust, dirt, or ash (from cooking with coal/wood, etc.), which can account for a sizable portion (in some cases 20%+ of the waste stream) in low-income cities that rely on solid fuels. For instance, if households burn wood or charcoal for cooking, the ash ends up in waste and inflates the inert fraction. Overall, low-income country waste tends to be wet and heavy (high moisture content) due to the organics and contains fewer plastics and metals. This composition has implications: the high organic content means low-income cities have a strong opportunity for composting or anaerobic digestion, but the low calorific value of the waste can make technologies like incineration less feasible without supplemental fuel.

- **High-Income Countries:** In wealthier economies, the waste stream usually has a much lower share of organics – typically on the order of 20–40% organic material (Kaza et al., 2018). For example, municipal waste in many high-income cities is roughly one-third of food and green waste. The remainder is dominated by materials like paper, plastic, and other packaging waste generated by a consumer-driven economy. Paper and cardboard can comprise a significant fraction (often 20–30%) of MSW in developed countries, given the prevalence of paper packaging, newspapers, office paper, etc. Plastics also form a large and growing share – often 10–15% or more in high-income contexts (Kaza et al., 2018). Metals and glass, while present in the waste stream (each perhaps a few percent), are often well-recovered in some countries due to recycling programs, so their share in residual waste might be smaller. A typical profile for a high-income country's waste might be roughly: one-third organic, one-quarter paper, one-eighth plastic, and the rest split among glass, metal, textiles and others. An example cited in the World Bank's analysis is that in high-income cities, "dry" wastes like paper and plastic are much more prevalent than in low-income cities, reflecting the consumption of processed and packaged goods (World Bank, 2018). Overall, high-income MSW tends to be drier and more energy-dense, which can facilitate waste-to-energy incineration and also provides a strong basis for recycling programs (since a large fraction is recyclable material if separated).
- **Middle-Income Countries:** Middle-income countries (both lower-middle and upper-middle) fall in between these extremes, with intermediate characteristics. As incomes rise, the proportion of organic waste generally starts to decline as a percentage (though absolute quantities may still rise), while the fractions of paper, plastics, and multi-layer packaging waste increase. For example, an upper-middle-income country might have roughly 50–55% organic content, lower than a very poor country but still higher than a rich country (Kaza et al., 2018).. Its plastic and paper shares will be on the rise (perhaps each in the low teens percent). Data show that in lower-middle income contexts, organics often make up just over half of MSW (~50%), plastics around 10–12%, paper around 10%, etc., whereas in upper-middle incomes, organics might drop slightly below half and plastics/paper each approach 15% of the total (Kaza et al., 2018). In essence, as one moves up the income ladder, waste composition transitions from mostly biodegradable to increasingly diverse. A notable point is that the level of detail in waste composition data itself tends to improve

with income – higher-income cities often conduct detailed waste characterization studies (distinguishing dozens of categories), whereas lower-income cities may have less granular data (sometimes broadly grouping everything not organic as “other”) (Kaza et al., 2018). Table 2.1 presented the data of these compositions and Figure 2-7 illustrates these data.

Table 2.1 Typical MSW composition in low-income vs. high-income countries (percentage by weight). (Source: Kaza et al., 2018, World Bank)

Component	Low-Income (%)	High-Income (%)
Organic (food/green)	~56%	~32%
Paper and cardboard	~7%	~25%
Plastic	~6%	~13%
Metal	~2%	~6%
Glass	~1%	~5%
Others (e.g. ash, dirt)	~27%	~11%

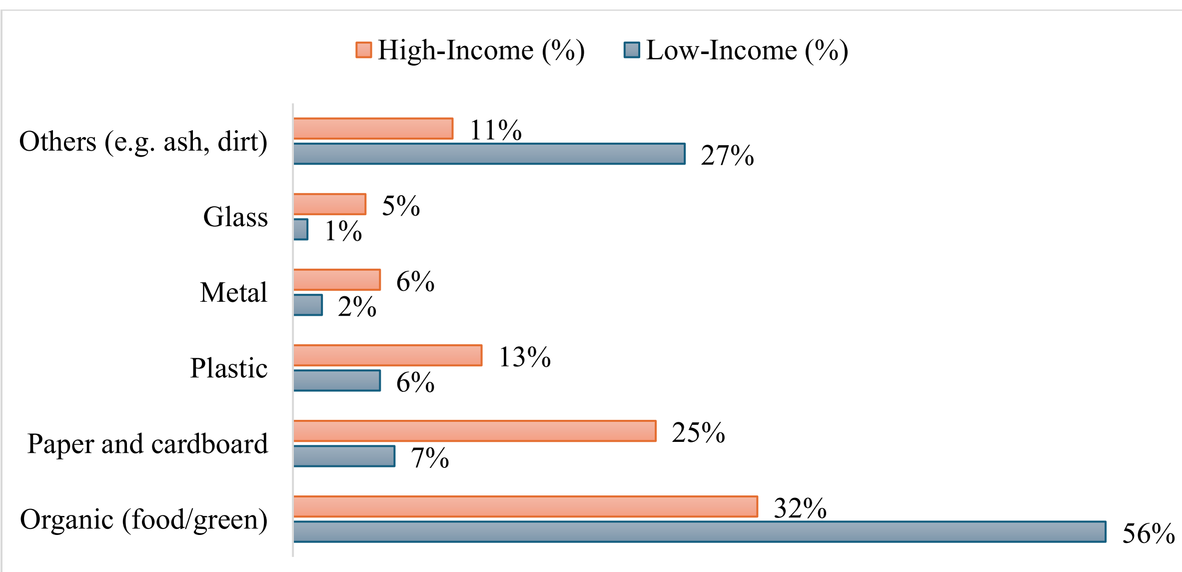

Figure 2-7: Typical MSW composition in low-income vs. high-income countries (percentage by weight). (Source: Kaza et al., 2018, World Bank)

The above trends have practical significance. In developing countries, the predominance of organic waste means that strategies like composting or bio-digestion could target the largest portion of the waste stream. Meanwhile, the lower share of plastics and paper might limit recycling potential unless collection systems improve. In developed countries, the diversity of materials (especially the significant plastic and paper fractions) has led to extensive recycling initiatives and also poses challenges in managing packaging waste. Importantly, as countries transition from low- to middle-income, their waste management systems often struggle to keep up with the changing composition – for example, the rise in single-use plastics and multilayer packaging can overwhelm nascent waste collection and recycling systems if not addressed. Understanding the composition of MSW across different economic groups is therefore crucial for designing appropriate waste management solutions, as will be discussed in subsequent sections comparing developed and developing country practices.

2.4 MSW Management Practices in Developed vs. Developing Countries

Municipal solid waste management practices differ markedly between developed (high-income) countries and developing (low- and middle-income) countries. These differences span the entire waste management chain: from collection coverage to sorting/recycling, to treatment and final disposal. The disparities are often driven by differences in financial resources, infrastructure, technology, and regulatory enforcement. Below is an overview of the typical practices and challenges in developed vs. developing contexts:

Waste Collection Coverage: In developed countries, waste collection services tend to have near-universal coverage. Municipalities (or their contracted companies) collect household waste at least weekly, and there are established systems for commercial and institutional waste collection as well. As a result, the vast majority of generated MSW in high-income cities is collected and removed from the point of generation. By contrast, in many developing countries, especially low-income nations, collection coverage can be incomplete – particularly in rural areas and informal urban settlements. According to World Bank data, low-income countries on average collect only about 48% of waste in urban areas and as little as 26% in rural areas (Kaza et al., 2018). This means roughly half of the waste in those countries may remain uncollected, often accumulating in streets, empty lots, or illegal dumps. Even in middle-income countries, while cities might achieve

80-90% collection coverage, remote or low-income neighborhoods can be underserved. The consequence of insufficient collection is open dumping of uncollected waste in the environment, leading to health hazards, clogged drainage, and pollution. Developed countries long ago established municipal collection as a basic public service (often dating back over a century), whereas developing cities are still expanding their service networks. Notably, many low-income countries allocate a significant portion of municipal budgets to try to improve waste collection – sometimes up to 20% of a city's budget – yet still cannot achieve full service coverage (World Bank, 2018). Improving collection in developing countries is an urgent priority, as uncollected waste is often the most visible and harmful aspect of poor waste management.

Recycling and Resource Recovery: Developed countries generally have more advanced systems for recycling and resource recovery from MSW. Many high-income countries have established recycling programs for paper, glass, metals, certain plastics, etc., supported by public awareness, separation at source, and recycling infrastructure. For instance, across the European Union, the average recycling rate of municipal waste is on the order of 30–50%, and some countries achieve even higher (Germany recycles ~67% of its MSW, one of the highest rates globally). Organic waste diversion (through composting or anaerobic digestion) is also practiced in many developed regions – e.g. many EU countries now separately collect biowaste. By contrast, in developing countries, formal recycling rates are typically much lower. The global recycling and composting rate was estimated at only about 19% of waste, and in low-income countries it's often a very small fraction of the waste that gets formally recycled (Ellis, 2018). However, an *informal sector* for recycling is often active in developing regions: armies of waste pickers, junk shops, and small recyclers recover materials like metals, cardboard, and certain plastics from the waste stream (either at the source or from dumpsites) to sell for reprocessing. This informal recycling can be significant even if it's not officially recorded. For example, in many Asian or African cities, thousands of people make a livelihood scavenging recyclables – their efforts may effectively recycle perhaps 5–20% of the waste, but without formal support it comes at a cost to their health and social conditions. Developed countries usually have moved beyond informal recycling to formalized systems (curbside recycling bins, deposit refund systems for bottles, etc.), which results in safer and often higher recovery rates for materials. Another aspect is **reuse and waste reduction**: high-income countries are increasingly implementing policies to reduce waste generation (like plastic bag bans, packaging regulations, food waste reduction campaigns), whereas developing countries, though traditionally having higher reuse of items (e.g. using refillable, repurposing containers), are now grappling with an influx of single use packaged goods.

Treatment and Disposal Methods: Perhaps the starkest differences appear in how final disposal is handled. In developed countries, open dumping of waste is virtually eliminated. MSW that is not recycled is disposed of in engineered sanitary landfills or incinerated in waste-to-energy facilities, or in some cases processed in advanced mechanical-biological treatment plants. Sanitary landfills in high-income countries are designed with liners, leachate collection, gas capture systems, and proper compaction and cover – all aimed at environmental protection. Incineration (with energy recovery) plays a significant role in places like Japan, Singapore, and parts of Europe where land is scarce; these facilities drastically reduce waste volume and can generate electricity, albeit at high capital and operating cost. In developing countries, by contrast, the predominant method of disposal is still uncontrolled dumping on land. It is estimated that 93% of waste in low-income countries is disposed of in open dumps or open burning, compared to only 2% in high-income countries (World Bank, 2018). Many cities in Africa and South/South-East Asia use dump sites that are essentially large open landfills with no lining or leachate control; waste is often just piled and occasionally covered with soil. These dumps frequently catch fire (either spontaneously due to methane or deliberately set alight to reduce volume), causing serious air pollution. The lack of environmental controls means that leachate from these dumps can contaminate groundwater and rivers, and they attract vermin and disease vectors. Middle-income countries may have some controlled landfills, but even there, enforcement of standards can be inconsistent. The World Bank notes that controlled disposal is almost exclusively the domain of upper-middle and high-income countries. For example, upper-middle-income countries landfill about 54% of their waste in controlled sites on average, whereas high-income countries landfill a smaller share (~39%) and divert much of the rest to recycling (35%) and incineration (22%). In low-income countries, by contrast, open dumping is by far the most common fate of waste. This gap underscores a major developmental challenge: closing the world's dumpsites and replacing them with sanitary landfills or other safe disposal methods is a priority for public health and the environment (Kaza et al., 2018).

Waste Management Infrastructure and Governance: Developed countries typically have well-established municipal bodies or private contractors handling waste management, with clear regulatory frameworks and funding mechanisms (e.g. waste collection fees or taxes). They often employ modern equipment (compactor trucks, transfer stations, treatment plants) and data systems to manage waste. Developing countries often face limited budgets, lack of equipment, and rapidly growing waste volumes that outstrip the capacity of local authorities. It is not uncommon for waste collection in some developing cities to be done with open trucks or even handcarts due to narrow streets and limited funds. Additionally, enforcement of anti-dumping laws or litter regulations may be weak. Another difference is long-term planning: high-income cities are moving towards integrated waste management (balancing reduction, recycling, energy recovery, and disposal, guided by the waste hierarchy of "reduce, reuse, recycle" and minimal landfilling). Many low-income cities, on the other hand, are in "crisis management" mode, focusing on simply removing waste from streets daily, with little capacity for recycling or future planning. International development agencies (e.g. World Bank, JICA) often assist these cities with technical expertise and financing to improve waste systems (for instance, constructing the first sanitary landfill or pilot recycling schemes).

Environmental and Health Outcomes: As a result of the above differences, the impacts of MSW management differ. Developed country systems, while not perfect, significantly mitigate direct public health risks—epidemics of garbage-related diseases are largely a thing of the past in those countries, and environmental controls reduce pollution (though landfill methane and resource loss are concerns). In developing countries, inadequate waste management contributes to clogged drains and urban flooding, breeding of mosquitoes and rodents (spreading malaria, dengue, cholera, etc.), respiratory problems from smoke, and other health issues especially among the urban poor who often live near dumps or work as waste pickers. The infamous example of dumpsite collapses (such as the Koshe dump landslide in Ethiopia 2017, or frequent fires at India's Deonar dump) highlight the human toll of substandard waste disposal. Recognizing these issues, many developing cities are now attempting to emulate aspects of developed-world practices – for instance, some are introducing controlled landfill sites, community recycling programs, and public-private partnerships for waste services. Yet, challenges like rapid urban population growth, limited funding, and institutional weaknesses make progress difficult.

In summary, developed countries generally exhibit high rates of waste collection, formal recycling programs, and reliance on sanitary landfills or incinerators for disposal, supported by strong governance and funding. Developing countries often struggle with incomplete collection, widespread open dumping, informal sector-driven recycling, and minimal treatment of waste. The gulf between these scenarios is gradually narrowing as developing nations invest in modern waste management, but significant disparities remain. Bridging this gap is essential for global environmental health, as mismanaged waste in any part of the world can lead to marine pollution, greenhouse gas emissions, and other transboundary issues. The next section will zoom into a local case study – that of Erbil City – to examine how these global patterns manifest in a specific developing urban context, and what progress and challenges are present there.

2.5 Municipal Solid Waste Situation in Erbil City

2.5.1 Population and waste generation rate

Erbil City, the capital of the Kurdistan Region in northern Iraq, provides a representative example of MSW management challenges in a developing urban context. Erbil has experienced rapid population growth and urbanization in recent decades. As of the early 2020s, the city's population is estimated at around 900,000 inhabitants (with roughly 1.5 million in the larger Erbil province) (Aziz, 2023). This growing population, along with rising living standards, has led to a substantial increase in municipal waste generation. Recent assessments indicate that Erbil city (and its environs) generates on the order of 1,700–2,000 (or in better way 1962 tons per day based on the statement of director of the Services and Environment protection) tons of municipal solid waste per day. This equates to an average waste generation rate of approximately 1.3–1.4 kilograms per person per day in Erbil, which is relatively high for the region. In fact, the per capita waste generation in Erbil province (about 1.33 kg/capita/day) exceeds the global average of 0.74 kg/day and even slightly surpasses the overall Iraqi national average (around 1.2–1.3 kg/day). The high generation rate in Erbil reflects the city's economic growth and consumer habits; it is comparable to what might be observed in some upper-middle income cities globally (Baban, 2023).

To put the figures in perspective, by 2023 the daily waste arriving at Erbil's disposal site was projected to reach roughly 2,400 tons (Baban, 2023). Two decades ago, these numbers were significantly lower, illustrating a sharp upward trend. A study comparing household waste generation over time found that in Erbil, the average household waste generation per person nearly doubled from about 0.62 kg/day in 2007 to 0.92 kg/day in 2021 (Aziz, 2023). This increase aligns with the city's population growth and lifestyle changes, including more consumption of packaged foods and disposable products. Overall, Erbil's waste generation trends are on the rise, putting pressure on the city's waste management system.

2.5.2 Waste composition in Erbil

The composition of Erbil's municipal solid waste reflects a mix of traditional organic waste and an increasing share of modern consumer waste (plastics, packaging, etc.). According to a JICA-supported waste analysis for 2020, food waste is the single largest component, constituting roughly 31% of Erbil's MSW by weight (Baban, 2023). This is a substantial organic fraction, though notably lower than in many other cities of Iraq where organics often exceed 50%. The next major component in Erbil is plastic waste, which accounts for about 28% (27.7%) of the total municipal waste. This category includes various plastic materials (bags, packaging, containers, bottles, etc.) and indicates the growing prevalence of plastic use in the city's commerce and daily life. Together, food waste and plastics make up nearly 60% of Erbil's waste stream. The remainder is composed of other materials: a significant portion is likely paper and cardboard, along with smaller fractions of metals, glass, textiles, and miscellaneous debris. While precise percentages for each of these other categories were not cited in the summary, one can infer that paper and cardboard could be on the order of 10–15%, and other combustibles/inerts (wood, leather, rubber, ash, etc.) collectively around 15–20%. For instance, a comparable waste profile (Baghdad in 2020) was reported as 42% organic, 21% paper, 21% plastic, and the rest glass/metal/others. Erbil's profile with 31% organic and 28% plastic suggests perhaps a higher paper fraction than Basra (which had over 54% food waste). In any case, Erbil's waste composition indicates a more "modern" waste stream relative to some other Iraqi cities – lower organic share and higher plastics, likely due to differences in consumption patterns in the Kurdish region and possibly more food waste reduction at the household level (or informal use of food scraps as animal feed, etc.).

It's worth noting that Erbil's organic fraction, at about one-third, is still substantial in absolute terms (some 600 tons of food waste is discarded daily in Erbil and surrounding areas, according to local news reports (Mirautsa, 2024). This volume of biodegradable waste presents both a challenge (it contributes to odors, leachate, and methane at the dumpsite) and an opportunity (it could be composted or digested to reduce landfill load). The high plastic content (nearly 28%) is a growing concern, as plastic waste does not degrade and is prone to litter the environment; it also increases the volume of waste significantly. The composition data underscores the need for Erbil to develop targeted strategies, such as organic waste separation for composting and enhanced recycling for plastics and paper.

2.5.3 Current waste collection and disposal practices

Erbil's municipality is responsible for waste collection in the city, which is managed by the Erbil Municipal Services and Environmental Protection departments. Collecting the waste of the city is divided into 12 zones, 6 for city center and others to the vicinity. The city's waste collection system primarily involves curbside collection of mixed waste from households and businesses. Residents generally dispose of their waste in bins or communal containers, which are then collected by municipal trucks. Coverage in the urban center is high – estimates suggest that the vast majority of Erbil's urban waste gets collected (on the order of 80-90% or more in the city center). Indeed, about 1,760 tons per day of waste were collected in Erbil province in 2020, which closely matches the estimated generation for the serviced population, indicating efficient collection in covered areas. However, some peripheral or informal areas might have less regular service, and rural parts of Erbil governorate have lower coverage. Collection in Erbil is done daily in many districts, using 600 garbage trucks operated or supervised by the municipality. The waste is not sorted at the source – it is collected as a mixed stream. Street sweeping and cleaning of public areas contribute additional waste that is also gathered by the municipal teams (Baban, 2023).

One challenge noted by local officials is the lack of sorting or separation during collection – all waste streams (food, recyclables, etc.) are mixed, which complicates later recycling or processing. The city has relied on conventional collection without significant waste segregation programs to date. Financing of waste collection comes from municipal budgets; Erbil reportedly spends 1.427 billion Iraqi dinars per month on waste management services of city center. And also, cost of disposal of the waste is 100 million dinars. Private sector involvement in primary collection appears limited, although secondary transport or certain services might be outsourced. The capacity of the collection system has been under pressure as waste quantities grow – media reports have highlighted that each month about 60,000 tons of garbage are collected from Erbil city (roughly consistent with 2,000 t/day) and taken to the landfill (Kurdistan24, 2021). Manpower, fuel costs, and equipment maintenance are ongoing concerns, but the city has thus far managed to prevent major accumulation of uncollected waste in the streets. There are occasional shortfalls – for example, if trucks break down or fuel is scarce – but generally Erbil's main issue lies not in collection, but in what happens after collection (Baban, 2023).

Waste Disposal – Kani Qirzhala Landfill: The collected MSW from Erbil is transported to a dumpsite known as Kani Qirzhala, located about 12 km west of Erbil city. This site has been the primary disposal location for Erbil's waste for roughly 17 years (since around 2006–2007). Kani Qirzhala is essentially an open landfill (only nominally a "sanitary" landfill, as it lacks many sanitary features). It covers an area of about 37 hectares (approximately 0.37 km^2), and over the years the waste piled there has reached a height of around 35 meters. The landfill has received hundreds of thousands of tons of waste per year; an estimate from late 2022 indicated an annual intake of ~328,500 tons (which is ~900 tons per day, but current daily intake is double that, suggesting the figure was a historical average). By 2023, local reports indicated that roughly 75% of the site's capacity has been utilized, leaving only about 25% remaining space for future waste. At current disposal rates, this remaining capacity could be filled in just a few years, raising concerns about where Erbil's waste will go next unless a new landfill is opened or the current site is expanded (Baban, 2023).

The Kani Qirzhala dumpsite lacks many environmental protections. According to evaluations, out of 23 standard criteria for a proper sanitary landfill, the Erbil site met only 7. There is no evidence of an engineered liner or leachate collection system, so it is likely that leachate (the liquid that drains from decomposing garbage) has been seeping into the ground and potentially affecting soil and groundwater. Likewise, landfill gas (methane) is not collected; instead, it often escapes freely or contributes to fires. Indeed, the site has been prone to smoldering fires and occasional large blazes. Residents have reported that in recent years, smoke from burning trash at Kani Qirzhala sometimes covers nearby areas; for example, in August 2023 a major landfill fire blanketed parts of the region with noxious smoke for days (Baban, 2023). The open burning (whether spontaneous or deliberate) releases toxins and greenhouse gases, posing health risks. Scavenging is also a common scene at Kani Qirzhala – numerous informal waste pickers, including children, roam the site to recover recyclables under unsafe conditions (Rudaw, 2025). Attempts by authorities to secure the site (e.g., by blocking entrances or proposing to fence it) have not fully stopped the scavenging or unauthorized dumping at its peripheries. Overall, Kani Qirzhala functions as an *uncontrolled landfill*, reflecting the typical situation in many developing cities where the main dumpsite is overburdened and under-engineered. It worth noting that, to prevent any fires, 200 wells of varying depths were drilled at the disposal site to collect the methane gases. But, because the piping system was very expensive and the gas production was very unstable, it was not possible to collect it and burn it in a generator and unfortunately it was forced to be burned.

The **environmental and health impact** of Erbil's current disposal practice is a growing concern. Beyond air pollution from fires, the decomposing organic waste generates methane (a potent greenhouse gas) contributing to climate change, and the accumulation of plastics and other non-biodegradables creates long-term contamination. The Kurdistan Region's environmental authorities have warned that the continued reliance on this dumpsite without improvements could lead to an "ecological catastrophe" (Baban, 2023). Leachate from the landfill has likely been polluting nearby soil and possibly groundwater, and the site attracts vermin and stray animals. These issues underscore the need for intervention.

Recycling and Waste Diversion in Erbil: Until recently, Erbil did not have formal recycling facilities or large-scale waste diversion programs. The Rudaw Research Center (2023) report explicitly notes that *"Erbil province lacks recycling facilities"* at present. All collected waste has been going to the landfill with minimal segregation. That said, there is evidence of some level of material recovery happening: the informal sector (waste pickers at the dump and perhaps itinerant scrap collectors in the city) does extract certain recyclables like metals, cardboard, and hard plastics. Additionally, a 2023 academic study pointed out that plastics, metals, cartons, and even tyres are being recycled in Erbil to some extent, with collected recyclable materials used as raw materials for new products (Aziz, 2023). This likely refers to private recycling enterprises that buy segregated scrap. For example, scrap metal yards will purchase metal recovered from waste, plastics might be collected and sent to small recycling factories (there are known plastic recyclers in Kurdistan that melt down plastic for pellets), and used cardboard is often bailed for recycling. These activities, however, have been informal or market-driven rather than municipally organized. The impact on the overall waste stream is modest – one study noted that such recycling reduced the volume of waste disposed by about 12% in terms of density, but the majority of waste still ends up landfilled (Aziz, 2023).

Encouragingly, city officials have signaled moves toward improving recycling. In a recent interview (March 2025), the head of Erbil's Environmental Protection department mentioned that a recycling plant will soon begin operations in Erbil, aiming to process all waste so that "nothing will remain" at the landfill. While details were not provided, this suggests that the municipality, possibly in partnership with a private firm, is setting up a materials recovery or waste processing facility. If realized, such a facility could sort mixed waste to recover recyclables and possibly treat organics (for example, by composting or biodigestion), significantly reducing the load on Kani Qirzhala. As of the writing of this chapter, this plant is not yet operational, but its planning indicates a shift in policy towards integrated waste management. Public awareness campaigns and pilot projects in waste separation may need to accompany the introduction of recycling facilities to ensure sufficient feedstock quality (Aziz, 2023).

Municipal Initiatives and Challenges: The Erbil authorities, including the Erbil Municipality and the Kurdistan Regional Government's Board of Environment, are aware of the waste management challenges. There have been discussions about finding a new landfill site (as the current one nears capacity) and upgrading waste management practices. One proposal has been to construct a proper sanitary landfill to replace Kani Qirzhala and to close and rehabilitate the old dumpsite. However, securing land for a new landfill and the necessary funds has been difficult. Another challenge is institutional: waste management in Erbil involves coordination between the municipality (under the Ministry of Municipalities) and the environmental authorities. Efforts to impose regulations (for example, preventing scavengers or open burning) have had limited success due to socioeconomic conditions (poverty drives scavenging) and lack of enforcement capacity. Moreover, while Erbil's waste generation is high, cost recovery is low – residents do not directly pay adequate fees for waste services, meaning the system is underfunded and relies on government budgets. This is a common scenario in developing cities, where waste services often operate at a financial loss, limiting expansion and improvements (Baban, 2023.

Summary of Erbil's MSW situation: Erbil City exemplifies a locale in transition. Its waste generation is rising toward levels seen in much wealthier cities, its waste composition is gradually shifting to include more plastics and packaging, yet its waste management infrastructure remains underdeveloped. The city has achieved a reasonable measure of success in collection – keeping streets mostly clear of accumulating garbage – which is commendable given the volumes. However, the downstream management (lack of recycling and reliance on an overflowing open dump) presents serious environmental issues. If no action is taken, Erbil could face worsening pollution and a waste disposal crisis as Kani Qirzhala reaches full capacity. On the other hand, plans for new facilities and recognition of the problem are positive signs. The situation in Erbil mirrors that of many fast-growing cities in developing regions: the need to leap from basic waste collection to a modern, sustainable waste management system. International support (such as JICA's study and recommendations) and local political will be crucial to implement solutions such as establishing a sanitary landfill, launching city-wide recycling and composting programs, and raising public awareness to reduce waste generation. In doing so, Erbil can move towards aligning with global best practices in MSW management while addressing its local realities.

Chapter Three

MSW Management Techniques

3.1 Waste Collection and Segregation Strategies

Waste collection is the foundation of any MSW management system, ensuring waste is transported from the community to treatment or disposal sites. **Segregation at source** – separating waste into categories (e.g. recyclables, organics, residuals) at the point of generation – is now widely recognized as an integral component of sustainable waste management (Trushna *et al*., 2024). Source segregation improves the safety and efficiency of downstream processes by reducing hazardous exposures and contamination in mixed waste. *For example, one study found that implementing household waste sorting could reduce landfill loads and cut waste-related carbon emissions by over 60%.* However, achieving high participation in segregation programs remains a challenge in many regions, particularly those lacking adequate infrastructure or public awareness (Zhang et al., 2021).

Municipal collection systems vary in design, but generally fall into two broad approaches:

- **Door-to-door collection:** Waste is collected directly from households (or businesses) on a regular schedule. Residents set out bins or bags (often sorted by waste type), and collection crews or trucks retrieve them from the curbside. This method tends to achieve higher collection coverage and can be paired with source-segregated bins for recyclables, organics, etc., yielding cleaner material streams for recycling. It does, however, require substantial logistical coordination and resources for frequent pickups.
- **Communal drop-off or bring points:** Residents carry their waste to central bins or collection points (e.g. street containers or transfer stations). Segregated containers may be provided (such as separate igloo bins for glass, paper, metals). This approach can lower collection costs but relies on public compliance and may suffer from issues like overflowing bins or illegal dumping if not well-managed.

Effective waste collection also increasingly employs technological innovations. Many cities are adopting **route optimization and smart collection systems** – using GPS tracking, sensors in bins, and data analytics to improve efficiency and reduce costs (Zhang *et al*., 2022). For instance, “smart bins” with fill-level sensors can signal when they need service, and AI-driven route planning can reduce fuel use and greenhouse gas emissions from collection trucks. Such innovations help address logistical challenges, especially as waste quantities grow.

Segregation strategies work in tandem with collection. The most common approach is to provide different colored bins or bags to sort waste fractions (e.g. green for organics, blue for recyclables, black for general waste), coupled with public education. Top-down regulations (like mandatory recycling laws) combined with bottom-up public awareness campaigns have proven effective in encouraging household compliance (Zhang *et al*., 2022). Community engagement is crucial: programs often include school curricula, media campaigns, and economic incentives or penalties. For example, pay-as-you-throw schemes (charging fees based on unsorted waste volume) and deposit-refund systems for bottles directly motivate waste reduction and sorting at the source. Studies have shown that providing information and immediate feedback can improve household sorting accuracy. In addition, convenience is a key factor – easily accessible bins and user-friendly sorting guidelines significantly increase participation (DiGiacomo *et al*., 2018).

Despite these efforts, **challenges remain**. In many low- and middle-income regions, waste collection is not universal, and open dumping is still widespread. Over **70% of countries** worldwide continue to use open dumps for a majority of their waste (Ozbay *et al*., 2021). This lack of segregation and controlled collection leads to serious issues: uncollected garbage in streets and waterways, and mixed wastes in dumps generating leachate and toxic smoke from spontaneous fires. Even in developed systems, improper sorting by residents can result in contamination (for example, food waste in recycling bins), which reduces the quality and marketability of recovered materials. Maintaining public motivation over time is difficult – without continuous education and convenient services, initial gains in segregation can stagnate or decline. Thus, waste authorities must implement ongoing community engagement and provide feedback on program outcomes (e.g. recycling rates achieved) to sustain high participation (Stoeva & Alriksson, 2017; Varotto & Spagnolli, 2017). In summary, collection and segregation strategies form the backbone of MSW management, enabling subsequent recycling and treatment processes to function effectively. Successful programs integrate robust infrastructure, policy incentives, and public education to achieve high rates of waste separation at the source.

3.2 Recycling and Waste Minimization Approaches

Recycling and waste minimization are central to moving towards a circular economy in MSW management. The well-known "**waste hierarchy**" (Reduce–Reuse–Recycle, often expanded to include Recovery and Disposal) ranks waste management strategies by environmental preference: waste prevention and reuse are top priorities, followed by recycling, with disposal (landfilling) as a last resort. This hierarchy, illustrated in Figure 3.1, underlines modern waste policies worldwide, emphasizing that the most effective way to manage waste is to not produce it in the first place.

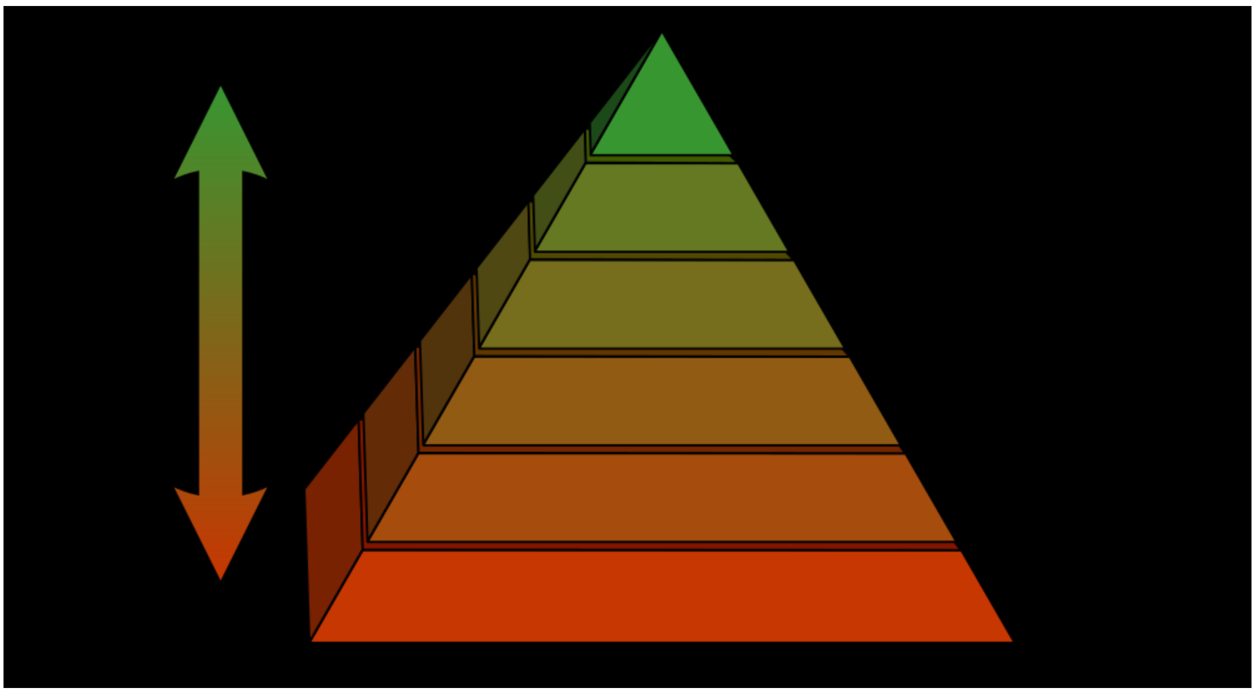

Figure 3-1 The waste management hierarchy ranks strategies from most preferred (top) to least preferred (bottom). Reduction of waste generation and reuse of products (top, green tier) are prioritized over recycling and energy recovery, while disposal in landfills

Recycling is the process of collecting and processing materials that would otherwise be discarded and transforming them into new products. Common recyclable materials in MSW include paper, cardboard, glass, metals, certain plastics, and increasing electronic waste. Recycling diverts these materials from landfills, conserving raw resources and reducing pollution from virgin material extraction and manufacturing. It is widely recognized as a cornerstone of sustainable waste management, as it lowers the overall environmental footprint of the waste system (Faraca *et al*., 2019). For example, recycling metals and glass saves substantial energy compared to producing them from ore, and recycling paper reduces deforestation and water use. According to Xiao *et al*. (2020), recycling is an integral step toward a circular economy, offering low energy consumption relative to the benefits gained (Zhang et al., 2021).

Recycling programs typically involve a materials recovery facility (MRF) where mixed recyclables are sorted (by machines and/or manual picking) into separate streams of paper, plastics, metals, etc. Efficient upstream segregation greatly aids this process; cleaner input streams result in higher quality recycles. A critical aspect of recycling approaches is addressing contamination – non-recyclable items or food residue can spoil entire batches of recyclables. For instance, food-soiled paper or mixed plastic types can render materials unrecyclable. Thus, public education often stresses proper rinsing of containers and keeping certain materials out (e.g. plastic bags can tangle sorting machinery). In regions with longstanding recycling systems, technologies like optical sorters, eddy current separators (for non-ferrous metals), and air classifiers are employed at MRFs to achieve high throughput sorting with improved purity (Zhang et al., 2021).

While recycling focuses on managing waste that has already been produced, waste minimization (or waste reduction) aims to *prevent* or reduce the amount of waste generated in the first place. This is the top-tier strategy in the waste hierarchy. Waste minimization approaches include designing products and packaging to use less material, promoting the use of durable and repairable goods over disposable ones, and encouraging consumer behaviors such as buying in bulk (to reduce packaging waste) and opting for reusable items (bags, bottles, etc.). From a policy perspective, governments have introduced measures like bans or levies on single-use plastics (to cut down on disposable waste generation) and extended producer responsibility (EPR) laws that require manufacturers to take back or fund the recycling of their products, thereby incentivizing them to design for easier recyclability and longer lifespans. Studies have shown that activities higher up the hierarchy, such as reuse, can yield greater environmental benefits than recycling because they avoid the resource use and emissions associated with producing new goods (Diprose et al., 2022). For example, reusing a glass bottle eliminates the energy that would be needed to crush and re-melt it into a new bottle.

A practical waste minimization approach in many communities is the promotion of compostable or recyclable packaging and product reuse schemes. For instance, container deposit systems (for beverage bottles) effectively increase reuse/recycling rates by attaching a refundable fee to packaging. Similarly, some cities facilitate swap markets or repair cafes to extend the life of consumer products, thereby reducing the waste that needs managing. Public participation in such waste minimization efforts is crucial – as Ozbay *et al*. (2021) note, encouraging individuals to *"minimize their ecological footprints"* through conscious consumption is part of comprehensive waste management.

In summary, recycling and waste minimization are complementary approaches: recycling deals with waste after it is generated, recovering value and redirecting materials back into the economy, whereas minimization strategies strive to curb the volume and toxicity of waste produced. Together, they help reduce the burden on downstream waste treatment and disposal facilities. A robust MSW management plan will prioritize waste avoidance and reuse, then maximize recycling of the waste that is generated, before resorting to energy recovery and landfill for the residuals. By following the waste hierarchy and continually improving recycling technologies and markets (e.g. developing better recycling methods for complex materials like multi-layer plastics or electronics), municipalities can move toward more sustainable, circular waste management systems.

3.3 Composting and Biological Treatment of Organic Waste

Organic wastes – such as food scraps, yard trimmings, paper, and other biodegradable materials – typically constitute a large fraction of MSW. In many cities, organics make up 40–60% of the waste stream by weight. Managing this organic fraction is crucial because when organics are landfilled or left in dumps, they decompose anaerobically and produce methane, a potent greenhouse gas. Biological treatment technologies harness natural decomposition processes to treat organic waste in a controlled manner, yielding useful products (like compost or biogas) and significantly reducing environmental impacts. The two primary biological treatments for MSW organics are composting and anaerobic digestion, which can be used independently or in combination (Trushna et al., 2024).

Composting is the controlled aerobic decomposition of organic materials by microorganisms (bacteria, fungi, actinomycetes). In composting facilities, organic waste is typically shredded and placed into piles or vessels where air flow, moisture, and temperature are managed to optimize microbial activity. Over weeks to months, the microbes break down the waste into a stable, humus-like product known as compost. This compost can be used as a soil amendment, returning nutrients and organic matter to soils. Composting offers multiple environmental benefits: it reduces methane emissions by diverting organics from anaerobic decay in landfills, and it recovers nutrients and carbon into a form that can enhance soil health (Manea *et al*., 2024). By stabilizing organic matter, composting also minimizes the production of leachate and odors compared to untreated waste disposal. Economically, composting can extend landfill lifespans (by reducing the volume going to disposal) and even provide revenue if the compost is sold for agriculture or landscaping (Manea *et al*., 2024).

However, there are challenges and limitations to large-scale composting of MSW. One issue is contamination of the input organics with plastics, glass, or hazardous substances – if not properly source-separated, the resulting compost may contain shards of glass or residues of chemicals/heavy metals, limiting its usability. Manea *et al*. (2024) note that the presence of heavy metals and microplastics in feedstock is a concern, requiring careful monitoring and sometimes preprocessing of waste (e.g. removing unsuitable items). Another challenge is controlling the composting process to prevent nuisances: without proper aeration and turning of compost piles, odors and even methane can be generated, and there is a risk of attracting vermin or flies. High-quality composting requires maintaining optimal moisture and temperature; this often means investing in infrastructure like aerated static piles or in-vessel composters, which can entail significant capital and operating costs. Additionally, not all organic waste is best suited for composting – certain types like meat or dairy waste can cause odor or pathogen issues if not handled carefully, and woody wastes decompose very slowly unless chipped. Despite these challenges, many cities and towns operate successful composting programs (e.g. curbside “green bin” collection of food and yard waste) that substantially reduce landfill inputs and produce useful compost (Manea et al., 2024).

Anaerobic digestion (AD) is a complementary biological treatment where organic waste is broken down by microbes in the absence of oxygen, producing biogas (a mixture of methane and CO_2) and a residual digestate. AD is commonly used for sewage sludge and agricultural wastes, but it is increasingly applied to the organic fraction of MSW (OFMSW), especially food waste. In an AD facility (often called a biogas plant), organic waste is loaded into sealed reactors where it undergoes a series of microbial stages (hydrolysis, acidogenesis, methanogenesis) yielding biogas. The **biogas** can be combusted in generators to produce electricity and heat or refined into biomethane fuel. This energy recovery is a major benefit of AD – it treats waste and simultaneously generates renewable energy. For example, digestion of one tonne of food waste can produce roughly 100–150 m^3 of biogas, which can generate on the order of 200–300 kWh of electricity. By capturing methane in a controlled system, AD avoids the uncontrolled release of methane that would occur if the organics decomposed in a landfill. The process also leaves behind a nutrient-rich **digestate** (the solid/liquid residue) which can be further composted or used (after appropriate treatment) as a fertilizer or soil conditioner, closing the nutrient loop (Trushna et al., 2024).

Anaerobic digestion shares some challenges with composting: it requires relatively contamination-free inputs (plastics and metals must be screened out beforehand), and the digestate may need post-treatment (e.g. dewatering, composting, or curing) to stabilize it and ensure any pathogens are destroyed. AD systems tend to be more capital-intensive than open composting (due to the sealed reactors, gas handling systems, and energy generation equipment), but they can be cost-effective when energy revenues and tipping fees are accounted for. Many modern organic waste management facilities actually combine AD and composting in a two-stage process: first an anaerobic digester extracts energy (biogas) from the waste, then the digestate is composted to produce a higher-quality soil amendment. This integrated approach can maximize resource recovery from organics (He et al., 2024).

In addition to traditional composting and AD, there are **emerging biological treatments** worth noting. **Vermicomposting**, for instance, uses worms (commonly Eisenia fetida, the red wiggler worm) to break down food scraps and other organics into high-quality worm castings, a nutrient-rich fertilizer. Vermicomposting is generally done on a smaller scale (household or community level) but has been explored for larger operations as well. Another innovative approach is the use of **black soldier fly larvae** to consume organic waste; the larvae convert waste into biomass (which can be used as animal feed protein or processed into biodiesel) and a frass residue that can be used as fertilizer. These biological methods are still niche in MSW management but represent creative ways to handle organic waste with potential circular economy benefits (e.g. producing insect protein). Mechanical-Biological Treatment (MBT) systems also exist, where mixed waste is mechanically sorted to extract recyclables and the remaining organic-rich fines are biologically stabilized (via composting or bio-drying) before landfilling. MBT is especially used in regions where source segregation is low, as a way to reduce the environmental impact of the residual waste (Manea et al., 2024).

Overall, composting and other biological treatments are vital for managing the organic component of MSW sustainably. By turning trash into useful products like compost, biogas, and soil amendments, these techniques contribute to climate change mitigation (through methane avoidance and renewable energy generation) and support soil conservation efforts. The key to successful implementation is maintaining clean input streams (often via effective segregation in Section 3.1) and choosing the right process or combination of processes for the local context. With ongoing improvements – such as better odor control technologies, microbial additives to enhance decomposition, and co-digestion strategies that combine food waste with wastewater sludge or animal manure for higher biogas yields – biological treatment of MSW is becoming increasingly efficient and attractive worldwide.

3.4 Incineration and Waste-to-Energy Technologies

Incineration is a thermal treatment process in which waste is combusted at high temperatures, converting it into ash, flue gases, and heat. When coupled with energy recovery systems, incineration becomes **waste-to-energy (WtE)** – the heat released by burning waste is used to produce steam that drives turbines for electricity generation, and sometimes to provide direct heating (in cogeneration or district heating setups). Modern waste incineration plants operate at furnace temperatures of 850–1100°C, ensuring nearly complete combustion of organic matter. The volume of solid waste is reduced dramatically (by ~90% in volume and ~70–80% in mass), greatly decreasing the amount of material that requires landfilling (Brunner & Morf, 2024). Historically, incineration has been employed as a solution for urban waste when land is scarce and to eliminate the health hazards of open burning or gross putrefaction – indeed, the introduction of incinerators in the 19th century improved city sanitation and reduced the spread of disease from accumulated refuse (Brunner & Morf, 2024).

Benefits and modern advancements: Today's WtE facilities are highly engineered and optimized for both energy recovery and environmental protection. A well-run incineration plant can generate 500–600 kWh of electricity per tonne of MSW incinerated, alongside potential recovery of heat for local use. Brunner and Morf (2024) emphasize that current WtE is *"one of the best investigated and optimized technologies in waste management,"* capable of safely destroying organic pollutants and reducing waste to inert residues. One major advantage of incineration is the destruction of hazardous organic compounds: pathogens in medical waste, contaminated or spoiled food, pharmaceuticals, and other difficult wastes can be completely combusted, thereby preventing them from entering the environment. Incineration also concentrates and encapsulates heavy metals and other inorganic pollutants into the ash, which can then be stabilized or landfilled safely, rather than leaching through an entire mass of waste. Another benefit is energy diversification – WtE provides a form of renewable energy (the biogenic portion of MSW is considered renewable) and can reduce reliance on fossil fuels for power generation.

Modern incinerators are equipped with sophisticated air pollution control systems to mitigate emissions. Flue gas passes through systems such as electrostatic precipitators or fabric filters (to capture particulate matter), acid gas scrubbers (neutralizing HCl, SO_2), selective catalytic or non-catalytic reduction units (to reduce NOx emissions), and activated carbon injectors (to adsorb mercury and dioxins). As a result, emissions from WtE plants have been drastically reduced compared to the past – dioxin emissions, for example, are a tiny fraction of what they were in the 1980s, thanks to better combustion control and flue gas treatment. Incinerator bottom ash (IBA), the chunky residue left after burning, can often be processed to recover metals (steel, aluminum, even small amounts of precious metals from electronics) and the mineral fraction used in construction (for example, as road base material), further contributing to resource recovery. Recent developments have even enabled the recovery of phosphorus from incineration of sewage sludge and the **carbon capture** from WtE flue gas, which could make WtE a net reducer of greenhouse gases when paired with bioenergy carbon capture and storage (BECCS) (Brunner & Morf, 2024).

Drawbacks and considerations: Incineration has long faced environmental and social concerns. Early incinerators often emitted significant air pollutants, leading to public distrust. Past experiences showed that while incineration solved the problem of excessive waste volume, it *"often created new and sometimes even worse problems"* in terms of air pollution (e.g. emissions of smoke, soot, toxic flue gases) (Brunner & Morf, 2024). Although technology has advanced, careful operation and monitoring are essential to ensure emissions remain within strict limits. Public opposition to new incinerators is common due to fears of pollutants like dioxins, furans, heavy metals, and fine particulates, as well as concerns about noise, odor, and traffic from waste trucks. Building trust through transparent communication of emissions data and regulatory oversight is necessary. Additionally, WtE plants are capital-intensive projects – they require high upfront investment and a continuous waste supply to be economically viable. This raises the concern that incinerators could create a demand for waste (to feed the plant) which might undermine recycling and waste reduction efforts if not managed by policy (a concept known as the "lock-in" effect). To counter this, many regions with WtE set high recycling targets and reserve incineration capacity only for non-recyclable, calorific wastes.

Another issue is the management of incineration ash. For every 100 tons of waste incinerated, about 20–30 tons of bottom ash and 2–5 tons of fly ash/air pollution control residue are produced. Bottom ash, after metal recovery and aging (to allow toxic compounds to stabilize), can sometimes be reused, but fly ash is classified as hazardous waste due to concentrated heavy metals, dioxins, and soluble salts captured from the flue gas. Fly ash must be handled and disposed of in specialized landfills or treated (e.g. by washing or solidification) to prevent leaching of toxins. Thus, incineration does not eliminate the need for landfills; it *reduces* and *transforms* the waste into a smaller, more inert form that still requires safe disposal or utilization.

Waste-to-energy technologies beyond mass-burn incineration: In addition to conventional grate incinerators, several advanced thermal technologies have emerged to recover energy from waste. Pyrolysis and gasification are two such processes that thermochemically treat waste in low-oxygen environments to produce fuel gases, oils, or char, rather than direct combustion to ash. In gasification, waste is partially oxidized at high temperatures (often 800–1000°C) with limited oxygen, producing a combustible syngas (primarily CO, H_2, and CH_4) and a solid residue of char/ash. Pyrolysis involves heating waste in the *absence* of oxygen, causing it to decompose into syngas, liquid oils/tars, and charms. These methods aim to extract more versatile energy products: the syngas can be cleaned and used in gas engines or turbines for higher efficiency power generation or even processed into chemicals; the pyrolysis oils can potentially be refined into fuels. Research indicates that pyrolysis and gasification of MSW or refuse-derived fuel can achieve higher energy recovery efficiency and lower air pollutant emissions compared to direct incineration, while also producing value-added outputs (Alfè *et al*., 2022). For example, Alfè *et al*. (2022) report that gasification of pre-processed MSW can reduce pollutant formation and yield syngas that is easier to clean, thereby mitigating dioxin and NOx issues at the source. These technologies, however, are less mature in the municipal waste context and often face operational challenges (feedstock heterogeneity, tar production in gasification, etc.). A few demonstration and commercial plants exist worldwide, but pyrolysis/gasification has not yet been adopted at the same scale as incineration for MSW. They also produce residual solids (char, slag) that need disposal or utilization. Plasma arc gasification is another cutting-edge method where an electrical plasma is used to reach extremely high temperatures, vaporizing waste into syngas and vitrifying the inorganic fraction into a glassy slag. It promises very clean outcomes but at a high energy cost and complexity.

In implementing WtE, a balanced, critical approach is needed. Incineration should ideally handle the fraction of waste that remains after all practical recycling and composting – it is most justified for treating non-recyclable plastics, contaminated or composite materials, and as a sanitation measure for certain wastes (like medical waste or sewage sludge). When used appropriately, WtE complements recycling by reducing the volume of true “residual” waste and recovering energy from it. Many European countries, for instance, have achieved high recycling rates alongside substantial WtE utilization, largely eliminating the need for landfills. Brunner & Morf (2024) argue that WtE plays an indispensable role in a circular economy by providing a "safe final sink" for problematic organic pollutants (destroying them) and by minimizing the need for landfill of hazardous inorganics through volume reduction and metal recovery.

Nevertheless, it is crucial to continually improve these technologies. Ongoing innovations include higher efficiency energy recovery (e.g. using supercritical steam cycles or integrating waste boilers with existing power plants), co-incineration of waste with biomass or coal (in cement kilns or power plants) as a way to utilize existing facilities, and integration of carbon capture on WtE plants to trap CO_2 from flue gas. If carbon capture is applied to biogenic waste emissions, WtE could even achieve net-negative emissions, helping mitigate climate change while managing waste (Ozbay et al., 2023)..

In conclusion, incineration and related WtE technologies provide a powerful tool for MSW management, drastically shrinking the waste volume and generating useful energy. They represent the **"recovery"** step in the hierarchy (after recycling), extracting energy value from waste that would otherwise be lost. The trade-offs include high investment costs and the need for vigilant pollution control, as well as ensuring that the push for energy recovery does not overshadow waste reduction and recycling efforts. With stringent regulations and advances in technology, modern WtE plants can operate cleanly and efficiently, making them a viable component of an integrated waste management system, particularly for densely populated areas with limited landfill space.

3.5 Landfilling: Traditional vs. Modern Approaches

Landfilling is the final repository for MSW that cannot be otherwise recycled or recovered. It involves the disposal of waste by burying it in the ground or piling it in engineered mounds. Traditional landfilling, often in the form of open dumps, has been the most common waste disposal method globally but is also the least preferred option in the waste hierarchy due to its potential environmental hazards. In contrast, modern sanitary landfills are engineered facilities designed to contain and isolate waste from the environment. This section compares the two, highlighting how contemporary approaches have evolved to mitigate the many problems associated with old dumping practices.

Open dumps (traditional approach): In an open dump, waste is unloaded on any convenient parcel of land without protective measures. This was historically the default method in many places and, alarmingly, remains prevalent today – by some estimates, over 70% of countries still use open dumping as their primary waste disposal method (Ozbay *et al*., 2021). Open dumps are essentially uncontrolled waste heaps; they lack liners, leachate management, or gas collection. The waste is exposed to rainfall and scavenging animals, leading to a slew of environmental impacts: leachate (the liquid runoff from waste) percolates into the soil and contaminates groundwater with organic pollutants, nutrients, and heavy metals; air pollution occurs from frequent fires (some dumps are intentionally ignited to reduce volume, others catch fire spontaneously from methane or heat) releasing smoke laden with particulate matter and toxins; and the uncovered waste attracts vermin (rats, flies) and disease vectors, posing public health risks to nearby communities. The sight and smell of open dumps also degrade quality of life. A tragic consequence of dumpsite mismanagement is the occurrence of landslides or structural collapses of waste piles, which have caused injuries and fatalities in some instances.

Socially, open dumps often become sites of informal scavenging – in many low-income countries, communities of waste pickers manually recover recyclables from dumps to sell for income. While this provides a form of resource recovery, it exposes workers (including children, in some cases) to dangerous health conditions. Overall, open dumping is highly unsustainable and unsafe, effectively passing on environmental costs to future generations. Recognizing these issues, virtually all high-income countries phased out open dumps decades ago, replacing them with regulated landfills or incineration. Some developing countries are now making similar transitions, though progress is uneven.

Controlled and sanitary landfills (modern approach): A sanitary landfill is an engineered site designed to isolate waste from the environment until it stabilizes. Modern landfills have several key features that distinguish them from dumps (Ozbay *et al*., 2021):

- **Engineered liners:** The landfill pit is lined at the bottom and sides with low-permeability materials, typically a combination of compacted clay and high-density polyethylene (HDPE) geomembranes. This liner system acts as a barrier to prevent leachate from seeping into soil and groundwater. Above the liner, a drainage layer (gravel or geosynthetic) is placed to channel leachate to a collection system.
- **Leachate collection and treatment:** As waste decomposes, leachate is captured by a network of perforated pipes at the base of the landfill (on top of the liner). This leachate is pumped out and treated (either on-site via leachate treatment plants or off-site at wastewater treatment facilities) to remove contaminants before safe discharge. Regular monitoring of groundwater around the landfill is conducted to ensure the liners function and no leakage is occurring (Ozbay et al., 2023).
- **Waste compaction and covering:** Unlike an open dump where waste may just be piled, sanitary landfills operate in "cells." Incoming waste is spread in layers and compacted by heavy machinery (landfill compactors) to reduce volume and increase stability. At the end of each day, a layer of soil or alternative daily cover (e.g., tarps, foam) is applied over the waste. This daily cover minimizes odor, deters pests, and prevents windblown litter. By controlling the active face of the landfill, the environmental nuisances are greatly reduced compared to an open dump.
- **Landfill gas management:** As organic waste in a landfill decomposes anaerobically, it produces landfill gas (LFG) – roughly 50% methane and 50% CO_2, with trace compounds. In modern landfills, a series of vertical wells or horizontal collectors are installed through the waste mass to capture this gas. The collected LFG is either flared (burned off in a controlled way to convert methane to the less potent CO_2) or, increasingly, utilized as an energy source (cleaned and used to generate electricity or processed into pipeline-quality

renewable natural gas). Capturing landfill gas not only prevents uncontrolled greenhouse emissions and explosion hazards but also provides an energy benefit from the waste. Many landfills generate substantial electricity from biogas – for example, a large landfill can power thousands of homes with its gas recovery system (Vaverková, 2019).

- **Final capping and aftercare:** When a landfill cell is filled to capacity, it is sealed with a multilayer **cap** consisting of clay or geomembrane (to keep water out), a drainage layer, and a top-soil layer for vegetation. This final cover prevents rainwater infiltration (which would generate leachate) and confines the waste. Even after closure, a landfill requires decades of monitoring for leachate and gas. Wells around the site track any contaminants in groundwater, and gas wells continue to operate until gas production declines to safe levels. Post-closure care typically extends for 30 years or more as a regulatory requirement in many countries.

These engineered measures mean that a modern sanitary landfill has a vastly lower environmental impact than an old dump. Studies have shown that leachate from well-lined landfills poses minimal risk to groundwater when properly managed, and that virtually all landfill gas can be captured with a well-designed system. The concept is to contain waste, transform it biologically over time, and protect the surrounding environment in the meantime. Engineered landfills are sometimes described as “dry tombs” – especially older designs which tried to minimize any moisture ingress to slow decomposition and contain waste – but more recent thinking on sustainable landfilling has evolved (Ozbay et al., 2023).

Traditional vs modern landfilling practices also differ in operational philosophy: Traditional landfills (and even early sanitary landfills) often sought to minimize biological activity (by keeping the waste as dry and compact as possible) to reduce leachate generation. This indeed limits immediate pollution, but it means the waste remains largely undecomposed for a very long time – essentially entombed – and will continue to pose a contamination risk if the containment systems ever fail in the far future. In contrast, bioreactor landfills represent a modern approach where conditions in the landfill are managed to accelerate waste decomposition. This can involve recirculating collected leachate back into the waste mass to maintain optimal moisture for microbial activity, or even injecting air in some sections (aerobic biocells) to speed up stabilization. The idea is that by enhancing the natural breakdown of organic matter within a decade or two, a bioreactor landfill can generate more landfill gas for energy and reach a stable state faster, potentially allowing earlier end of aftercare. Two types are often mentioned: anaerobic bioreactors, which add moisture (sometimes supplemented with nutrients or special microbial inocula) to boost methane generation; and aerobic landfills, where air is introduced to reduce methane production and compost the waste in situ. These techniques are still being optimized, but they exemplify the innovative mindset in modern landfill management – treating landfills not as static dumps, but as managed waste treatment reactors (Ozbay et al., 2023).

Environmental protection and regulations: Modern landfills operate under strict regulations that govern location (e.g. away from aquifers and floodplains), design (liner and cap specifications), operation (covering, vector control, prohibited wastes), and monitoring. For instance, hazardous wastes are typically not allowed in MSW landfills (they go to specialized hazardous waste landfills). Only certain types of stable industrial wastes might be co-disposed if they meet criteria. Regular inspections and reporting are mandatory. These regulations were lacking for traditional dumps. The improvement is clear when comparing outcomes: a well-run sanitary landfill produces controlled emissions and leachate that can be collected and treated, whereas an open dump passively pollutes the environment. Modern landfills also integrate features to reduce their footprint, such as planting vegetation on closed sections (turning them into green mounds that can be used as parks or wildlife habitat) and installing systems to collect and flare gas even during operation.

Despite all advances, landfilling remains the last resort in waste management. Even the best landfill is a temporary containment – the waste is still there, requiring eternal vigilance. Liners and caps will eventually degrade (albeit over decades or centuries), and the burden of monitoring can stretch long into the future (Vaverková, 2019). In a truly sustainable system, the goal is to minimize what goes into landfills to only those materials that have no better use. Landfills do serve an essential role as a "sink" for residual waste and materials that cannot be recycled (Brunner & Morf, 2024). For instance, certain hazardous inorganics (like asbestos or certain industrial sludges) are safely sequestered in lined landfills. Moreover, landfills will always be needed as a backup for waste emergencies (e.g. disaster debris) and for the solid residues from other waste processes (incinerator ash, non-compostable rejects, etc.) (Brunner and Morf, 2024).

Looking at **traditional vs modern practices** side by side, the contrast is stark. Traditional dumps were essentially uncontrolled, resulting in groundwater contamination, frequent fires, foul odors, and disease proliferation. Modern landfills, through engineering and management, address each of those issues: leachate is collected and treated rather than contaminating groundwater, waste is covered to prevent fires and odors, gas is captured to prevent uncontrolled emissions, and public exposure to waste is minimized. Ozbay *et al*. (2021) documented those countries which invested in modern landfilling (or alternatives) dramatically improved environmental outcomes, while those still reliant on dumps face escalating pollution and health crises. The move from traditional to modern landfilling is therefore a fundamental step in improving a region's waste management (Ozbay et al., 2021).

Finally, there is interest in future landfill management such as *landfill mining* – excavating old landfills to recover valuable materials or to remediate sites. In some cases, old dumps near urban centers have been mined for recyclables or to reclaim land, coupling the process with the construction of a new sanitary landfill for the excavated material. This approach remains rare and technically challenging, but it symbolizes the changing perception of landfills: not as untouchable final resting places for waste, but as repositories that might be tapped or re-engineered as technology and economics permit.

Integration with overall MSW management: The role of landfilling in an integrated system is to handle what remains after all feasible reduction, reuse, recycling, and recovery. In a well-managed city, this should be a shrinking fraction over time. For example, high-income countries with mature systems might landfill less than 10% of MSW, whereas the global average is still around 40% or more (with lower-income regions landfilling or dumping most of the waste). Modern approaches seek to continually reduce reliance on landfills – through policies promoting the upstream techniques discussed in previous sections – and to ensure that when landfilling is used, it is done in the most responsible manner possible (Ozbay et al., 2021).

3.6 Erbil situation in MSW management

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Chapter Four

Landfilling Technologies and Challenges

4.1 Types of Landfills

4.1.1 Open Dump Landfills

Municipal solid waste disposal sites vary widely in design and control. In low-income regions, **open dump landfills** are common, where waste is simply deposited on land with little or no engineering. Such dumps lack liners, covers, or gas systems, and often allow free access by scavengers (Remigios 2010). Because they are unregulated, open dumps quickly contaminate soil and groundwater with pollutants leached from waste, and produce uncontrolled gas emissions. Open dumps are prevalent where resources for engineered sites are scarce (Remigios 2010; Siddiqua *et al.* 2022). People living or working near these sites face exposure to hazards (e.g. disease vectors, fires, toxic smoke) as no containment measures exist.

4.1.2 Semi-Controlled Landfills

represent a partial improvement. These are designated dumping sites where basic management is applied. Waste is placed in a confined area, compacted, and often covered with soil or other material on a daily or periodic basis (Remigios 2010). Some rudimentary organizations (fencing, patrols) is provided, but critical protections are still missing there is typically no engineered liner to block leachate, and no leachate collection or gas control systems are installed. In practice, a semi-controlled site may simply use a prepared area of ground (sometimes leveled or trimmed) and impose minimal cover. The aim is to reduce odors and pests by covering garbage, but these landfills generally allow much leachate seepage to underlying soils. Semi-controlled landfills are an intermediate step in waste management; they are more systematic than open dumps but far less protective than modern sites.

4.1.3 Sanitary Landfills

Sanitary landfills are engineered disposal facilities designed to minimize environmental impacts. In a sanitary landfill, refuse is placed in thin layers, compacted, and covered with soil or alternative daily cover materials (Siddiqua *et al.* 2022). Modern sanitary landfills use composite bottom liners made of compacted clay and synthetic geomembranes (Jain *et al.* 2023), which serve to intercept and isolate leachate. A leachate collection system (perforated pipes within a drainage layer) is installed above the liner to collect contaminated liquid for removal and treatment. Gas control is also integral: gas recovery wells or vacuum systems are embedded in the waste to capture methane and other landfill gases. These gases are often flared or utilized for energy. Sanitary landfills are subject to regulatory standards (e.g. Subtitle D in the US) that dictate final cover construction (usually a thick clay/geomembrane cap with topsoil and vegetation) and long-term monitoring. Because of these features, sanitary landfills contain most pollutants and monitor their own stability (Jain *et al.* 2023; Siddiqua *et al.* 2022).

4.1.4 Bioreactor Landfills

Bioreactor landfills are an innovative variant of sanitary landfills that actively enhance decomposition. In a bioreactor landfill, moisture (often recirculated leachate or added liquid) and sometimes air or nutrients are deliberately injected into the waste mass to accelerate biological breakdown. By maintaining high moisture and optimal conditions, a bioreactor can dramatically speed waste stabilization (Benson *et al.* 2007). Unlike conventional "dry tomb" designs (which minimize moisture), bioreactor landfills may reach full decomposition in years or decades instead of centuries. They produce stronger leachate (higher BOD/COD) initially and often generate methane more rapidly. In practice, bioreactor operation involves pumping leachate back into the cell through wells or trenches and monitoring enhanced settlement and gas production. Bioreactors are still relatively rare but are considered an advancement toward more sustainable landfilling, because they reduce long-term aftercare (faster stabilization means a shorter monitoring period) and increase renewable energy (methane) recovery.

4.2 Landfill Design and Operations

Landfill engineering involves multiple systems to protect the environment. A typical modern landfill is designed with layered protection: (1) Liners at the base prevent waste leachate from percolating to groundwater; (2) a leachate collection system transports any liquid to central collection; (3) gas collection wells capture methane; and (4) a final cap covers the closed landfill (Jain *et al.* 2023). Cells are filled in sequence and compacted, while operations are carefully monitored. Figure 4.1 illustrates a cross-section of a sanitary landfill and its main components.

Figure 4-1 Schematic cross-section of a modern sanitary landfill, illustrating features such as a composite clay/geomembrane liner, leachate collection pipes, methane gas recovery wells, and final soil/vegetative cap (after Jain et al. 2023; Siddiqua et al. 2022).

4.2.1 Landfill Liners and Leachate Collection

The **liner** is the critical bottom seal that prevents contamination of surrounding soil and groundwater. As noted by Jain *et al.* (2023), modern landfills typically use either a single composite liner (a geomembrane atop compacted clay or a geosynthetic clay liner) or a double-liner system (two separate liner layers with a leak detection zone between). These barriers are designed to withstand punctures, tears, and deterioration. Over 98% of leachate is usually captured by the liner/collection system in well-designed landfills. Leachate (liquid draining through the waste) is collected via a network of perforated pipes laid on a gravel layer above the liner. This liquid is pumped out to treatment, so it cannot accumulate and exert pressure. The collection system also includes leak-detection drains in double-liner sites, which alert operators to any breakthrough (Jain et al. 2023).

Landfill **leachate** itself is a potent contaminant mixture. It contains dissolved organic matter, salts, ammonia, heavy metals, and often trace organics (Kjeldsen *et al.* 2002). Concentrations are highest during the early acid phase of decomposition, and may decline in a long-term methanogenic phase, but some constituents (especially ammonia and salts) persist (Kjeldsen *et al.* 2002). Left unchecked, leachate can pollute groundwater and surface water over decades. Thus, engineered liners and collection are essential controls to intercept leachate. Regular sampling of leachate and surrounding groundwater is performed during operations and for decades afterward to ensure compliance with environmental standards (Jain et al. 2023).

Table 4.1 Comparison of common landfill types and their control measures (adapted from Remigios 2010; Jain et al. 2023).

Landfill Type	Site Control Level	Engineering Features	Example Characteristics
Open Dump	None (uncontrolled)	No liner, no cover, no collection	Waste dumped in open pits; high exposure; minimal safety
Semi-Controlled	Partial (designated site)	No liner, some compaction/cover	Waste placed in managed cell; minimal daily cover
Sanitary	Full (regulated)	Composite liner, leachate & gas systems	Engineered layers, compacted fills, environmental monitoring
Bioreactor	Advanced (engineered + active treatment)	Same as sanitary + liquid recirculation	Elevated moisture to speed decomposition; increased methane

4.2.2 Gas Recovery Systems and Energy Utilization

Decomposing waste produces landfill gas (LFG), a mixture primarily of methane (CH_4) and carbon dioxide (CO_2). Methane is a potent greenhouse gas (≈28× CO_2 by potency) and is combustible. **Gas recovery systems** capture this LFG before it vents to the atmosphere, thus mitigating climate impact and providing energy. Perforated wells or horizontal collectors are installed in the waste body. A slight vacuum is maintained to draw gas into a header pipe. The gas is then either flared (burned to CO_2) or processed for use as fuel.

Recovered LFG can be valuable: it typically contains 45–60% methane and can be used to generate electricity, heat, or be upgraded to pipeline-quality renewable natural gas. Worldwide experience shows that well-operated gas collection can capture roughly 60–90% of the landfill's methane production (Scharff *et al.* 2024). Early implementation of gas collection yields the greatest mitigation benefit. Scharff *et al.* (2024) emphasize that initiating gas recovery soon after waste placement can significantly reduce long-term methane emissions. Indeed, modeling indicates that early recovery is one of the most effective mitigation measures (Scharff *et al.* 2024). In practice, landfill operators may install wells in the first operational cell after wasting the filling and extend the network as new cells are added. The gas is typically desulfurized, and moisture is removed before use. Electricity generation from LFG is common; the power can be sold or used on-site. Many governments incentivize LFG-to-energy projects due to both emission reduction and renewable energy goals.

4.2.3 Landfill Closure and Rehabilitation

When a landfill reaches capacity, it is closed and capped to isolate the waste. The closure process involves grading the waste surface, adding a final cover system, and revegetation. A modern closure cap usually consists of multiple layers: a low-permeability soil or geomembrane layer to block water infiltration, a drainage layer (often sand) to shed rainwater, and a topsoil layer to support grasses or other vegetation. The cover minimizes rainwater percolation that could generate new leachate. It also serves to contain gas, which continues to be collected via remaining wells. In colder climates, snow and ice cover must be managed.

After closure, landfills enter a post-closure care period. Regulatory programs commonly require monitoring for 30–60 years (sometimes longer) after closure to ensure the site is stabilizedmdpi.com. During this phase, operators test groundwater and gas emissions regularly, maintain any treatment systems, and keep the cover in good condition. If sites meet closure performance criteria (e.g. leachate generation declines to near-zero), active controls may eventually be reducedmdpi.com. Many closed landfills are later converted to beneficial uses: they may become parks, golf courses, or wildlife areas once gas migration has ceased. Some lands have been repurposed for renewable energy (e.g. solar farms). In rare cases, closed landfills are later mined for materials.

4.3 Environmental Impacts of Landfills

Landfills can impact the environment through leachate contamination, greenhouse gas emissions, and public health/social effects. These impacts vary greatly with site type, engineering, and management.

4.3.1 Leachate Contamination of Groundwater

Leachate is the liquid effluent from landfill wastes, and it can contain a cocktail of pollutants. It typically has high concentrations of dissolved organic matter (measured as BOD or COD), ammonium-N, chloride, iron, manganese, and other inorganic constituents (Kjeldsen et al. 2002). Xenobiotic organics and trace metals may also be present (Kjeldsen et al. 2002). Unlined or poorly lined landfills allow leachate to migrate, posing a major risk to groundwater. Even sanitary landfills rely on the integrity of their liner systems to prevent leakage. As a result, contamination of aquifers near landfills has been widely documented.

Studies (e.g. Siddiqua et al. 2022) note that improper landfill sites can cause elevated levels of nitrates, heavy metals (e.g. lead, cadmium), and other substances in nearby water. Groundwater pollution can occur decades after placement, because contaminants leach slowly. The severity depends on factors like site geology, rainfall, and waste composition. For example, a closed dump without a liner will often generate high-strength leachate that seeps downward until it reaches groundwater. Clay liners, composite liners, and leachate collection dramatically reduce this risk by intercepting leachate (Jain et al. 2023). However, even lined landfills require monitoring: over time, liner defects or degradation can allow small leakage. Therefore, monitoring wells are installed hydraulically downgradient of the landfill. If contamination is detected, remedial measures (pump-and-treat, barriers, etc.) may be needed.

4.3.2 Landfill Gas Emissions and Climate Change

Landfills are a significant source of anthropogenic methane. Globally, solid waste disposal in landfills contributes on the order of 18% of human-generated CH_4 emissions, and about 3–4% of total greenhouse gasespmc.ncbi.nlm.nih.gov. Methane arises from anaerobic decomposition of organic waste (food, paper, yard debris, etc.). If the gas is not captured, it is venting directly to the atmosphere, where methane's global warming potential is ~28 times that of CO_2 over a 100-year horizon. Thus, uncontrolled landfill emissions can substantially accelerate climate change. According to the IPCC, in many countries landfill CH_4 emissions have been historically underestimated because default recovery rates were assumed low (e.g. 20%).

Effective gas collection mitigates this impact. As discussed above, modern sites often capture most of the methane produced. Nonetheless, residual emissions (from inefficiencies or older dumps without gas systems) still occur. In addition to methane, landfills emit carbon dioxide (from decomposition and oxidation of methane) and non-methane organic compounds (NMOCs) in small quantities. These include volatile organic compounds (benzene, toluene, etc.), sulfur compounds (which cause odor), and trace toxic gases. While CH_4 is the major GHG concern, some of the NMOCs and trace substances are harmful air pollutants.

Climate models and field studies confirm the benefits of landfill gas projects. Landfills equipped with energy recovery can become net sinks (offsetting fossil fuel use) rather than sources of methane. For example, flaring or energy use of methane turns CH_4 into CO_2, reducing greenhouse impact by ~75% per unit of original carbon. The timing of gas capture is also important: early capture and oxidation is more climate-friendly than waiting decades (which many biogas models now assume). In summary, engineering controls (gas wells, flares, engines) significantly reduce a landfill's climate footprint (Scharff et al. 2024; Siddiqua et al. 2022).

4.3.3 Public Health and Social Concerns

Beyond chemical pollution, landfills have broader social and health implications. Open dumps and poorly managed sites can become breeding grounds for disease vectors such as flies, mosquitoes, rats, and stray animals. Waste pickers who work at such sites (sorting through garbage) face hazards: cuts, infections, and exposure to pathogens and toxic materials. The open burning of waste (often practiced at dumps) releases toxic smoke containing fine particulates and dioxins, posing respiratory risks to neighbors. Unpleasant odors and noise (from trucks and compactors) reduce quality of life for adjacent communities. Fears about health effects (cancer, respiratory illness, birth defects) from living near landfills have led to public opposition and anxiety, although epidemiological studies often show mixed evidence due to study limitations (Zein et al. 2022).

Controlled sanitary landfills still generate concerns: people living nearby may notice foul smells or fear groundwater contamination. Local property values can decline. Community engagement is often needed to address these issues. Regulatory agencies therefore impose strict monitoring and access controls. In many jurisdictions, public health departments require distance buffers from residences and provide landfill workers with safety equipment and training. Education programs warn communities about the dangers of scavenging or using landfill water.

Environmental justice is also relevant: historically, the poorest neighborhoods have tended to host dump sites. Efforts to site new landfills often face “NIMBY” opposition. Conversely, modern closed landfills repurposed as parks or solar farms can become community assets if properly managed. In all cases, transparent communication of risks and mitigation measures is crucial to address public health and social concerns associated with waste disposal.

4.4 Advancements in Sustainable Landfilling

The landfill sector is evolving toward sustainability through new technologies that recover resources and reduce impacts. Key advancements include refined bioreactors, enhanced gas-to-energy systems, and landfill mining.

4.4.1 Bioreactor Landfills

As noted, bioreactor landfill technology intentionally accelerates waste degradation by optimizing moisture and biological activity. Recent research has demonstrated that such systems can shorten the stabilization time of waste dramatically compared to conventional landfills. By recirculating leachate through the waste mass, bioreactors maintain uniform moisture and distribute nutrients. This promotes more rapid breakdown of organics into methane and carbon dioxide. Faster waste stabilization means the landfill reaches a “non-hazardous” state sooner, potentially reducing the required duration of post-closure care. Bioreactors also tend to enhance methane generation rates, enabling energy recovery sooner after waste disposal. However, they require careful design: excessive moisture can produce runoff or slope instability, and higher strength leachate must be managed. Despite these challenges, full-scale implementations have shown promise in improving landfill sustainability by turning a liability (leachate) into a resource (accelerated decomposition and energy)cues.rutgers.edu.

4.4.2 Landfill Gas Recovery for Energy Generation

Landfill gas-to-energy (LFGTE) projects are established technology for turning waste emissions into power. Modern systems go beyond simple flaring by using gas engines, turbines, or fuel cells to generate electricity. The captured methane is a renewable energy source that can offset fossil fuel use. Many advances have been made in gas utilization: for example, upgrading LFG to pipeline-quality biomethane for injection into natural gas grids, or compressing it for use as vehicle fuel. Advances in gas processing (dehumidification, H_2S scrubbing, carbon filtration) have improved the efficiency and cleanliness of these systems. Furthermore, combining LFG extraction with carbon finance (e.g. the Clean Development Mechanism) has spurred investment in landfills. In essence, landfill gas recovery has evolved from a mere mitigation tool to a revenue-generating enterprise that supports waste management economics (Scharff et al. 2024).

4.4.3 Landfill Mining and Resource Recovery

A more radical approach to sustainability is **landfill mining**, which involves excavating closed or active landfill cells to recover materials. In older landfills, valuable recyclables and combustibles (metals, plastics, biomass) remain trapped. By digging up waste, one can reclaim these materials for recycling or energy, and free up landfill space. Mining also allows for site remediation: the excavated waste can be properly sorted, stabilized, or landfilled in a controlled bioreactor mode. Research and pilot projects (Hoekstra 2013; Piatak *et al.* 2019) have shown that landfill mining can reduce methane emissions (by removing the source of organic decay) and extract metals and plastics for the circular economy. Though currently limited by economics and safety (e.g. dealing with unknown hazards in old waste), landfill mining exemplifies a shift in thinking: landfills are seen not just as waste repositories but as future resource reservoirs. It aligns with ‘waste-to-product’ concepts where even post-disposal waste is a potential feedstock for new use (Avinash & Mishra 2024).

Chapter Five

Challenges of MSW Management in Erbil City

5.1 Institutional and Policy Gaps

Erbil's solid waste management suffers from regulatory and institutional weaknesses. Like the rest of Iraq, Erbil is governed by waste regulations that are widely regarded as outdated and vaguely defined. Scholars note that Iraq's regulatory framework for solid waste is "outdated, poorly enforced, and lack[s] the necessary clarity" to address modern waste management needs. In practice, municipal services in Erbil operate under fragmented mandates: for example, municipal authorities oversee waste collection and landfill operation, but coordination with environmental and health agencies is limited. This fragmentation leads to inconsistent practices across city districts. Moreover, regulatory enforcement is weak – illegal dumps and unsanitary landfill operations proceed without sanction. In short, the existing policy environment provides little incentive or guidance for sustainable waste practices (Kareem et al., 2024).

At the local level, Erbil City's waste collection is handled by multiple private contractors across municipal zones, but without strong oversight. According to local data, six private companies collect an aggregate ~1,600–2,000 tons of MSW per day from Erbil's approximately 1.5 million residents. However, there is no systematic source-separation or formal recycling program mandated by regulation; all waste streams (household, commercial, construction) are simply mixed and dumped (Aziz et al., 2023). The one official landfill – Kani Qirzhala – is managed by the municipal Directorate of Services yet lacks modern design or regulatory control (see below). In the absence of clear legislation, responsibilities for waste reduction, recycling, and environmental monitoring fall between government agencies. Resources are further constrained by political and economic factors: Iraqi municipalities (including Erbil) "often struggle with budget constraints, making it difficult to invest in necessary infrastructure and services" (Kareem et al., 2024). Under such fiscal pressure, policy enforcement is deprioritized.

5.2 Infrastructure and Technical Limitations

Erbil's waste management infrastructure remains rudimentary. Collection and transport rely on an aging fleet of trucks, and virtually all refuse is hauled to the single main landfill at Kani Qirzhala.

Many municipalities “lack the necessary equipment and facilities” to handle growing waste volumestrendytechjournals.com, and Erbil is no exception. For example, waste bins and collection vehicles in Erbil’s neighborhoods are in short supply, leading to irregular pickup schedules and frequent service gaps. At the processing end, no transfer stations, sorting centers, or engineered treatment facilities exist within city limits. Instead, collected garbage (including organic, plastic, paper, and construction debris) is driven directly to the landfill without pre-processingpdfs.semanticscholar.orgijeijournal.com.

The Kani Qirzhala landfill – opened in 2001 about 15 km west of Erbil’s center – is Erbil’s only official disposal siteojs.wiserpub.com. It receives over 2,000 tons of mixed solid waste every day . However, the site functions as an open dump rather than a sanitary landfill. As one field report noted, waste is “disposed of in non-scientific landfill” conditionsijeijournal.com. There is no engineered leachate control, no gas collection system, and no cover for decomposing waste. In fact, researchers describe the site as using “an obsolete system, such as an open dumping system, rather than a modern … sanitary landfill”ojs.wiserpub.com. This technical inadequacy has already led to contamination: monitoring at Erbil’s dump has found that leachate plumes from the waste heap are seeping into nearby soil and water.

Besides the landfill, Erbil lacks basic recycling or treatment infrastructure. There are no formal composting plants for organic waste or waste-to-energy facilities in operation. Very little formal mechanical or biological treatment is conducted. In practice, only informal scavengers separate recyclables onsite. Studies report that all Erbil waste is mixed at collection, with only “a small fraction of recyclable materials (e.g. plastic, glass, metals) … separated by scavengers” at the dumppdfs.semanticscholar.orgijeijournal.com. For example, residents do not sort their garbage by type or recycling stream, so municipal trucks carry unsorted refuse (Aziz, 2023). This lack of sorting technology means the recovery of plastics and metals is left entirely to informal waste-pickers.

Another technical limitation is the absence of adequate medical and hazardous waste handling. In many developing cities, hospitals and industries can produce infectious or toxic waste, but in Erbil these are often co-mingled with municipal waste. No incinerator or secure hazardous-waste landfill is available. As a result, any medical or industrial wastes delivered to Kani Qirzhala mingle with everyday garbage, further increasing health and environmental risks.

Overall, Erbil's MSW infrastructure is rudimentary: collection is inconsistent, waste transport uses antiquated equipment, and disposal is via a basic open dump with no modern facilities. These deficiencies mirror those in other Iraqi cities, where "inadequate waste management infrastructure and services has led to the proliferation of illegal dumping sites and open burning"trendytechjournals.com. Until Erbil invests in robust technical systems – vehicles, transfer stations, sorting facilities, sanitary cells, etc. – the city's growing waste stream will continue to overwhelm the current dump.

5.3 Public Awareness and Participation

Public engagement in waste management is very limited in Erbil. Surveys and studies across Iraq consistently find low household awareness of proper MSW practicestrendytechjournals.com. Most Erbil residents view waste collection as the city's responsibility and have little knowledge of environmental laws or the benefits of recycling. Household waste is typically discarded in mixed bags or bins, with no home composting, recycling bins, or source-separation. Education campaigns on recycling or waste reduction are virtually non-existent. In short, there is little local demand for change: proper disposal and recycling are not yet social norms, so citizens rarely question the status quo.

Because of this, Erbil's recycling sector has remained informal. A few dozen waste pickers ("scavengers") work at the landfill and dumps, manually sifting through the rubbish to collect items of value. Formal collection of recyclables is negligible. A 2019 field study noted that "a small fraction of recyclable materials… are separated by scavengers on-site" at the Erbil dumpijeijournal.com. There are no curbside recycling services or buy-back centers run by the municipality. Likewise, residents and businesses typically do not sort their waste; the concept of separate glass, paper, or compost bins is not implemented by public authorities (Kareem et al., 2024).

This situation could change if public awareness increased. Experiences in other Iraqi cities suggest that many citizens are willing to engage if given infrastructure and information. For instance, a survey in southern Iraq found broad willingness "to participate in waste sorting if provided with the necessary infrastructure"trendytechjournals.com (Kareem et al., 2024). In Erbil, limited environmental education and weak enforcement mean such initiatives have not materialized. Some NGOs and media outlets have begun outreach on proper waste handling, but these efforts are nascent and piecemeal. Without consistent educational campaigns or incentives (like reducing collection fees for sorted waste), the population remains largely uninvolved (Kareem et al., 2024).

5.4 Financial Constraints and Investment Needs

Financial resources are a critical limiting factor in Erbil's waste sector. Like other Iraqi municipalities, Erbil operates on a tight budget for MSW services. The City of Erbil collects only modest fees (through local taxes and some landfill charges), and most operating costs come from its municipality budget. In practice, "municipalities often struggle with budget constraints, making it difficult to invest in necessary infrastructure and services"trendytechjournals.com. For Erbil, this means there is little capital available for new trucks, transfer stations, or landfill upgrades. International donors have funded some preliminary studies (e.g. design of a new sanitary landfill), but the city has been unable to allocate matching funds for construction.

These financial pressures translate into narrow margins for innovation. One recent study of collection efficiency in Erbil illustrated how tight the budget is. By optimizing a single waste collection route, researchers projected a mere 8.43% reduction in fuel use, saving only about $2,700 per year (Aziz et al., 2023). In other words, even small efficiency gains yield negligible cost savings, because the overall budget is already lean and labor costs dominate. This example underscores that modest improvements cannot solve Erbil's underfunding; substantially more investment is needed.

Investment needs in Erbil are extensive. Ideally, the city would upgrade Kani Qirzhala into a sanitary landfill (with liners, leachate treatment, and a gas capture system), build sorting and recycling centers, and expand its fleet of modern trucks. It would also implement waste-to-energy or composting projects to reduce reliance on dumping. However, these projects require millions of dollars in capital, far beyond Erbil's current budget. So far, most expenditures have gone to routine collection and to extend the existing dump area. Until Erbil secures dedicated funding (for example, through government grants or public–private partnerships), these infrastructure investments will remain unmet.

To date, the city has explored some revenue streams – for instance, selling some recyclables – but at current scale this yields only a few hundred dollars per day, insufficient to offset costs. Financial analysts emphasize that sustainable waste management in developing cities often requires external support. In Erbil's case, this might include low-interest loans or technical assistance from international agencies. Without such support, Erbil's waste services will continue operating just above subsistence level.

5.5 Illegal Dumping and Open Burning

Figure 5-1 A bulldozer working on an uncontrolled landfill site. Many developing cities (including Erbil) still rely on open dumping for MSW, lacking engineered controls or covered cells.

This figure above illustrates conditions at Erbil's principal dump: waste is left exposed, machinery simply pushes trash into piles, and no waste processing or compaction occurs. Such uncontrolled disposal areas inevitably lead to open burning (often practiced reducing volume) and leachate leakage. In fact, analysis of Iraq's cities confirms that inadequate collection and dumping infrastructure "has led to the proliferation of illegal dumping sites and open burning of waste" (Kareem et al., 2024). Observers in the Kurdistan Region similarly report that open burning is common, especially at landfills and roadside dumps, posing serious health and environmental hazards.

In Erbil, illegal dumping is both a symptom and cause of weak services. When municipal trucks or informal collectors cannot reach a neighborhood promptly, residents sometimes resort to dumping bags of garbage along vacant lots or ditches on the city periphery. These sites are unregulated and usually in poor condition. Official surveys are scarce, but environmental groups in Erbil note dozens of such “fly-tipping” locations, often where population has recently expanded. In the absence of formal waste transfer stations, some commercial haulers will also dump construction or bulky waste illegally to save tipping fees. Moreover, without enforcement, residents have little fear of dumping or burning. Open burning of accumulated garbage (especially plastics and organics) is a recurrent problem, particularly during the hot summer months. Such practices release toxic smoke and contribute to local pollution.

By contrast, cities with better regulations use fines and monitoring to deter these behaviors. In Erbil’s case, however, any enforcement agency is under-resourced. Waste inspections are rarely performed, and penalties for illegal dumping are minimal or nonexistent. Until Erbil invests in enforcement (training inspectors, surveilling known hotspots, and imposing fines), illegal dumps will remain a persistent challenge. This issue threatens to undermine any other improvements: new infrastructure or policies can be bypassed if waste continues to be dumped or burned informally.

Despite these challenges, some progress is possible. As waste management experts note, creating additional drop-off points and educating the public on the harms of burning can gradually reduce illegal dumping. In Erbil’s case, the expansion of the existing landfill (plus community clean-up programs) might offer stopgap relief. But ultimately, eliminating these problems will require the same institutional, technical, and financial reforms discussed above.

Table 5.1 Composition of Erbil City MSW (2023). Current waste streams are dominated by organic and plastic materials, with relatively small fractions of recyclables (Aziz et al., 2023).

Component	Percentage (%)
Organic material (food/yard)	35
Plastic	27
Paper and cardboard	14

Metals	2
Glass	3
Yard trimmings & wood products	3
Other (incl. textiles, debris)	16
Total	**100**

Chapter Six

Strategies for Sustainable MSW Management in Erbil City

Effective solid waste management in Erbil must build on the challenges identified in Chapter Five, namely weak policies, limited infrastructure, budget shortfalls, and low public engagement – and follow international best practices (waste hierarchy, circular economy). Following the UNEP waste hierarchy, the first priority is to prevent and minimize waste; where waste is generated, it should be treated as a resource (reused, recycled, composted) before resorting to disposal. The following sections outline a multi-pronged strategy for Erbil, integrating local conditions with global guidelines (UNEP, World Bank, UN-Habitat).

6.1 Policy and Regulatory Recommendations

Erbil must strengthen its legal framework and institutions to provide clear mandates and incentives for sustainable MSW management. First, municipal bylaws should be enacted or updated to require source segregation, ban open burning, and eliminate uncontrolled dumping. The polluter-pays principle should be explicitly adopted: waste generators (households, businesses, industries) must bear collection and disposal costs. Extended Producer Responsibility (EPR) regulations (for packaging, plastics, etc.) can incentivize waste reduction at the source. Economic tools such as landfill taxes, tipping fees, and differential collection charges (higher fees for mixed waste, discounts for separate recyclables) should be introduced to internalize environmental costs and generate revenue. Financial incentives – subsidies or soft loans for recycling, composting and waste-to-energy (WtE) projects – can stimulate private-sector investment. All new policies must be accompanied by strict enforcement provisions, compliance inspections, and penalties for violations.

- **Clarify institutional roles:** Assign responsibility for waste policy, oversight, and service provision to appropriate agencies. The Kurdistan Ministry of Municipalities and Public Works should lead strategic planning, while Erbil Municipality implements operational aspects. Coordination mechanisms (interagency committees) can avoid overlaps.
- **Standards and targets:** Set quantitative goals (e.g. % recycling, composting, reduced landfill disposal) in line with Iraq's national plan and SDG targets. Adopt environmental standards for waste facilities (emissions, leachate, etc.) as the "bottom line" for human health and environment (Hyman, 2013).

- **Integrated waste strategy:** Develop an official municipal waste management plan (in partnership with UN-Habitat/USAID expertise as has begun) that spans collection, processing and disposal, with finance, monitoring and community education components. This should align with Iraq's National Solid Waste Management Plan principles (e.g. waste hierarchy, polluter pays, precaution) and UN guidance on holistic strategies (Hyman, 2013).

These reforms must address the deficiencies noted in Chapter Five. For example, Aziz et al. (2023) highlight Iraq's "inadequate infrastructure [and] insufficient regulatory frameworks" as key barriers. Erbil should thus bolster regulations *and* the capacity to enforce them. As UNEP/UNITAR (2013) advises, legislation should be coupled with economic instruments and public education to change producer and consumer behavior. Engaging civil society (NGOs, schools, media) in policy development and outreach will build the social buy-in needed for new rules to succeed. Finally, integrating the informal sector – local waste pickers and recyclers – into formal programs can improve system efficiency and livelihoods. In summary, Erbil's regulatory strategy should enforce strict waste standards and fees (polluter-pays, EPR) while providing incentives and education to foster waste reduction and recycling (Hyman, 2013).

6.2 Improvement of Waste Collection and Segregation

Enhancing collection efficiency and expanding source separation are critical early steps. Erbil must expand and modernize its collection fleet and routing to achieve full coverage. This includes procuring sufficient collection vehicles (e.g. side-loader trucks) and establishing enough container locations or curbside service across all neighborhoods (urban and peri-urban). Collectors should follow optimized routes (using GIS-based planning) to minimize fuel use and missed pickups. In parallel, infrastructure for source segregation must be introduced: households and businesses need separate bins or bags for organics, recyclables, and residuals. Container depots or transfer stations can be set up where recyclables are aggregated. Pilot programs (in selected districts) can trial dual- or tri-bin separation schemes with public education, before city-wide rollout.

Experience in developing countries shows that at-source separation greatly improves recycling and reduces disposal volume. Given that over 50% of waste in developing cities is organic and compostable, Erbil should institute separate collection of food/yard waste. Organic waste can be picked up daily or every other day, using small, covered carts to avoid pests. Simultaneously, dry recyclables (paper, plastics, metal, glass) should be collected separately (at least weekly) to feed recycling processors. Incentives – such as lower collection fees for well-separated waste or small payments for recyclables – can encourage compliance. Enforcement (fines or service suspension for non-segregation) may be needed but should be phased in with education (Aziz et al., 2023).

Public participation is often lacking: one study notes that in Iraq the collection framework exists but "user support is scarce," leading to litter and dumping. Erbil's strategy must therefore include a sustained outreach campaign. Key messages should teach residents how to separate waste and explain the benefits (health, cleaner streets, resource recovery). Educational materials, demonstrations and school programs are effective. Over time, Erbil could involve community volunteers or cooperatives in neighborhood recycling drives and organics composting workshops. The collection companies could be required to hire or contract the existing informal waste pickers, formalizing their role (with training and protective gear) to increase sorted material recovery (Aziz et al., 2023).

In practical terms, the city should improve operational aspects as follows:

- **Coverage:** Ensure all areas (including informal settlements) are serviced regularly. Use smaller vehicles or collection points in narrow or remote lanes.
- **Sorting at source:** Mandate color-coded bins; provide bins and instructions to households and businesses. Collect organics in dedicated trucks to avoid contamination of recyclables.
- **Formalize recyclers:** Partner with recyclers to set up collection centers (buy-back or bring centers) where citizens can drop off sorted recyclables for cash.
- **Monitoring:** Track collection performance via records (tons collected per zone) and citizen feedback. Adjust service levels based on waste generation studies.
- **Behavior change:** Launch media campaigns and community outreach to build public awareness and pride in clean neighborhoods. Visible "zero litter" initiatives (clean streets events) can foster cultural change.

By ensuring reliable collection services and promoting waste segregation, Erbil can dramatically increase diversion from disposal. As the World Bank notes, separation of recyclables and organics makes subsequent composting and recycling far easier. Improved collection will also reduce illegal dumping; open dumping and burning become virtually unnecessary once door-to-door service with sorting is reliable (Hoornweg et al., 1999).

6.3 Enhancing Recycling and Composting

Given Erbil's waste composition (organics ≈35%, paper/plastics ≈40–50%), significant gains are possible through recycling and composting. Formal recycling infrastructure – material recovery facilities (MRFs) and compost sites – should be developed or upgraded. At the municipal level, the government can establish designated sorting centers where mixed recyclables are manually or mechanically separated into clean streams (paper/cardboard, plastics, glass, metal). These centers can be operated by the private sector under contract, supported by guaranteed-offtake agreements (e.g. MoUs with recyclers or industries that use scrap). Through such MRFs, much of the existing material now landfilled can be channeled back into the economy. Aziz et al. (2023) estimates that Erbil's recyclables (plastic, metal, paper) could yield hundreds of dollars per ton in revenue; harnessing this value requires institutional support and market links.

Organic waste should be processed by composting. Depending on scale, Erbil can employ:

- **Municipal compost facility:** A centralized aerobic composting plant (e.g. turned window or aerated static pile) where all collected organics are processed. This requires land, machinery, and moisture management.
- **Decentralized/community composting:** Smaller compost units at neighborhood or institutional level (markets, parks) for garden/market waste.
- **On-site/household composting:** Promote home or community compost bins for kitchen scraps (especially for peri-urban residents with gardens).

Composting has multiple benefits. It can divert roughly half of the waste stream from disposal, producing a nutrient-rich soil amendment that can improve local agriculture and landscaping. World Bank studies note that composting "produces a valuable soil amendment…integral to sustainable agriculture," reduces landfill methane, and enhances recycling operations by removing organics. Critically, diverting organics raises the purity of the remaining recyclables, improving their marketability. In Erbil's case, where food waste is abundant, a large-scale compost plant could transform a liability into a product (for sale to farmers, gardeners, etc.). The municipality should ensure quality by supporting training on proper mixing (C/N ratio) and by prohibiting contaminants (no plastics, metal in compost feedstock) (Hoornweg et al., 1999).

The recycling sector also needs formal support. Erbil should simplify permitting and potentially subsidize the establishment of sorting/recycling businesses. Public-private partnerships (e.g. municipal waste company financing a recycling unit run by a private firm) can leverage expertise and capital. Policies like reducing or eliminating customs duties on recycling equipment (glass crushers, ballers, plastic granulators) can help local entrepreneurs. Educational campaigns should emphasize the economic value of recyclables to spur "cleaner" separation. Over time, an integrated recycling network – linking waste pickers, collection centers, processing plants and manufacturing users – can be built.

6.4 Integration of Waste-to-Energy and Landfill Gas Utilization

Waste-to-energy (WtE) technologies offer additional options for Erbil's MSW, especially the organic fraction. However, global experience shows that WtE deployment must be carefully matched to local conditions. Erbil should pursue low-tech WtE first (e.g. biogas) before large-scale incineration. Two main pathways are recommended:

- **Anaerobic digestion (AD):** Food and yard waste can be treated in digesters to produce biogas (≈60–70% methane) and a nutrient-rich effluent. Biogas can fuel generators (electricity) or be upgraded to compressed gas. AD plants can be co-located with the compost facility or even at the landfill (in-situ digestion trenches). This is often more environmentally friendly than incineration. It avoids toxic emissions and produces fertilizer as a byproduct (Khan et al., 2022).
- **Landfill gas (LFG) capture:** As the existing and future landfill's organic waste decomposes anaerobically, it generates methane-rich gas. Engineering the landfill to collect and flare or utilize this methane is a proven method. Captured LFG can fuel an on-site generator or simply be flared (to convert CH_4 to CO_2, reducing greenhouse impact). As World Bank/IDB guidance notes, properly designed municipal landfills produce gas with ~50% methane; capturing this gas reduces potent emissions and provides an energy source (Cointreau, 2004).

Advanced WtE (incineration, gasification, pyrolysis) can be considered only after foundation steps are in place. Modern incineration (with energy recovery) requires stable, high-calorie waste and substantial investment in emissions controls. It also requires rigorous air pollution control (filtering dioxins, NOx). In fact, Khan et al. (2022) caution that incineration can be "expensive and inefficient… as it burns waste it emits NOx, mercury, dioxins… and undermines sustainable zero waste practice" (Khan et al., 2022). Given Erbil's high organic and moisture content, incinerators would struggle (lower calorific value) and may generate backlash over air quality. If pursued, strict emission standards and public consultation would be mandatory.

Instead, emphasis should be on **biogas and LFG**. Key actions include:

- **Pilot biogas projects:** Start a medium-scale digester for collected organics. Feasibility studies (perhaps with help from GIZ or USAID) can optimize design.
- **Upgrade landfill for gas recovery:** When expanding or replacing the Kani Qirzhala site, ensure engineered covers and gas wells are installed. According to IDB, "only well-managed and -operated landfills generate the expected amount of LFG". Daily soil cover, compaction and proper cell phasing are needed to concentrate gas flow to collection pipes (Cointreau, 2004).
- **Utilities linkage:** Develop a grid or electricity plan to use LFG/biogas generation on-site. Even a small 500 kW generator could utilize much of the landfill gas and supply institutional power (lighting, pumps).
- **SDG alignment:** Frame WtE projects in terms of climate and energy goals. Utilization of waste biogas contributes to SDG7 (clean energy) and SDG13 (climate action) (Khan et al., 2022).

The following **Table 6.1** summarizes the pros and cons of major WtE options, illustrating why Erbil should prioritize methane recovery and digestion over incineration.

Table 6.1 Comparison of major waste-to-energy (WtE) technologies (Khan et al., 2022; World Bank, 1996).

Technology	Feedstock	Output/Energy Carrier	Key Considerations

Incineration (Mass Burn)	Mixed MSW	Electricity/heat (high-temperature combustion)	High capital and operating costs; air emissions (NOx, dioxins); better suited for dry, non-organic waste.
Anaerobic Digestion (AD)	Organic waste (food, yard)	Biogas (methane) for power or fuel	Ideal for high-organic MSW; produces fertilizer byproduct; more environmentally friendly than incineration.
Gasification/Pyrolysis	Dried/sorted waste	Syngas (H_2/CO)	Emerging technology; requires waste pretreatment; lower air pollutants than incineration.
Landfill Gas Recovery	Decomposing MSW in engineered landfill	Methane-rich gas for power or flaring	Utilizes existing landfilled waste; requires impermeable cover, gas wells and pumping to collect gas.

By capturing biogas and LFG, Erbil can both mitigate methane emissions and obtain renewable energy. Any WtE project should be coupled with improved sorting (to remove inerts and recyclables first) and with environmental safeguards. Pilot and scale-up should proceed carefully, learning from international examples and engaging local stakeholders.

6.5 Developing a Sustainable Landfill System

Even with aggressive waste diversion, a final disposal site is needed for residuals. Erbil's existing Kani Qirzhala dump (an open pit opened in 2001) should be phased out and replaced with a fully engineered sanitary landfill. A "sanitary" landfill – meaning one with physical and operational controls – is essential to protect health and the environment. Key elements include: a thick compacted clay or geomembrane liner to isolate waste from soil/groundwater; leachate collection and treatment systems; gas collection wells; and systematic daily and final cover. Waste cells should be raised in layers, each covered with clean soil (or tarps/inert materials) each evening to prevent odors, pests and water infiltration (Cointreau, 2004). The landfill plan must incorporate surface water drainage, erosion control, and groundwater monitoring around the perimeter.

World Bank guidance emphasizes that sanitary landfills in developing cities must “provide for daily cover of fresh refuse, incorporate mitigative measures to manage leachate and gas produced within the landfill cells, provide for a final soil and vegetative cover, and establish an environmental monitoring system” (World Bank & WHO, 1999).. Erbil should follow these criteria. In particular:

- **Site design:** The new landfill (or the upgraded existing site) must have engineered liners and leachate drainage pipes. In our relatively arid climate, design may be somewhat relaxed (compared to a rainy region), but good practice dictates at least compacted clay liners and a leachate pond or treatment lagoon onsite. Soil test pits should confirm groundwater depth and infiltration rates (World Bank & WHO, 1999).
- **Leachate management:** A drainage system (sloped gravel collection) should capture leachate and convey it to storage ponds. Ideally, constructed wetlands or sequential anaerobic-aerobic treatment lagoons can treat the leachate before reuse (e.g. irrigation) or safe discharge. Preventing leachate leakage is vital, as open dumping has already caused local soil and possibly water contamination (World Bank & WHO, 1999).
- **Gas management:** The landfill should be developed in phases (cells) that age sequentially. Within a few years after waste placement, anaerobic decomposition generates high methane concentrations (~50%). Vertical gas wells and piping should be installed in each cell after it is filled to control gas flow. The gas can be collected to flare off safely or to fuel a generator. As IDB guidance stresses, *only well-managed landfills generate the expected amount of LFG* – good compaction, cover, and gas piping are needed (Terraza and Willumsen, 2010).
- **Operational controls:** A gatehouse with a weighbridge and records ensures all incoming waste is accounted for. Efforts should be made to divert recyclable or hazardous waste before landfilling (e.g. media-sorting or banning electronics). Staff training is crucial so that the landfill is compacted and covered daily, slopes are maintained, and unauthorized scavenging/settling is prevented.

- **Closure and reclamation:** Even after reaching capacity, the site should be capped with soil and planted with grass or shrubs to prevent erosion and infiltration. Plans must be made for post-closure maintenance and monitoring (e.g. gas vents) for decades. Wherever possible, closed sections can be repurposed (e.g. solar farm, park) consistent with guidelines.

Table 6.2: Recommended sanitary landfill design features (adapted from World Bank guidance) (World Bank & WHO, 1999)

Feature	**Description**	**Purpose**
Impermeable liner	Compacted clay or geomembrane under waste	Prevents leachate from entering soil/groundwater.
Leachate collection	Sloped gravel base and pipes to sump	Collects infiltrating water and waste liquids for treatment.
Daily cover	15–30 cm soil or alternate cover each day	Minimizes odors, pests, and water infiltration.
Gas collection system	Wells and piping in waste cells	Captures methane for flaring/energy; reduces emissions.
Monitoring wells	Groundwater and gas probes around site	Ensures early detection of any leaks or issues.
Access controls	Fencing, controlled entry, security patrols	Prevents unauthorized dumping; protects scavengers.

By investing in a well-designed landfill, Erbil will eliminate the health hazards of its current open dump. As the World Bank emphasizes, moving from open dumping to an engineered facility is critical for public health and environmental protection. Even modest upgrades (liners, cover, basic leachate handling) make a large difference and are feasible with international assistance. In the medium to long term, Erbil should "achieve full sanitary landfilling together with policies and programs to reduce waste generation and increase recycling" (World Bank & WHO, 1999). This integrated approach – combining waste diversion (from previous sections) with a safe final disposal – completes the loop toward a sustainable system.

Chapter Seven

Case Studies and Best Practices

7.1 Successful MSW Management Models from Other Cities

Municipalities worldwide have tailored solid waste systems to their unique contexts, yet certain features recur in successful models. A common theme is integrated waste management: planning that spans generation, sorting, collection, treatment, and disposal in a unified frameworkpure.qub.ac.ukc40.org. For example, in Pune, India (a city of ~3 million), the government partnered with the existing informal waste-collector cooperative (SWaCH) to manage MSW. Under this model, ~50% of Pune's waste is handled by thousands of door-to-door waste pickers operating under contract. They collect separated recyclables and organics, dramatically reducing what reaches landfills. The result is striking: SWaCH waste pickers recover about 30,000 tons of plastic annually, diverting roughly 52% of Pune's plastic waste from landfill and saving an estimated 50,000 tons of CO_2-equivalent per year (ENSCAP, 2019). This case demonstrates that harnessing local labor and incentivizing recycling (rather than only relying on municipal crews) can greatly improve diversion.

Another instructive example is Baku (Azerbaijan, pop. ~2.2 million). Baku historically suffered from open dumping and informal disposal. A World Bank–supported "Integrated SWM" project completely overhauled Baku's system (2008–2018). The old Balakhani dump was upgraded into a sanitary landfill with gas-collection, and over 170 informal dump sites were closeddocuments1.worldbank.org. This modernization expanded waste collection and disposal capacity, helping increase formal service coverage from ~60% to nearly 80%. The lesson here is clear: investment in engineered disposal facilities (sanitary landfill, leachate and gas control) can transform waste management in cities where uncontrolled dumping was the norm. Erbil could similarly benefit from upgrading its main dump into a modern, lined landfill and creating transfer stations (Waste, 2021).

Globally acclaimed cities also offer guidance. In Europe and North America, many cities now aim for "zero waste" through combined recycling and waste-to-energy. For instance, Swedish cities incinerate roughly half their municipal waste (59%) while recycling ~40%, thus sending <1% to landfilleea.europa.eu. Vienna (Austria) or Copenhagen (Denmark) likewise recycle or compost a high fraction of waste and capture methane from landfills for energy. These cities complement technology with strict policies: they mandate separation of organics and recyclables and charge households for non-recyclable trash. A useful summary from C40 Cities notes that successful systems rely on ambitious targets, integrated resource planning, and support for the circular economy. In practice, this means local laws, infrastructure, and education all work together. For example, public green bins for food waste and blue bins for paper are ubiquitous in many European cities.

Even in regions with fewer resources, model projects stand out. Hurghada, Egypt (tourist city) has introduced multi-bin collection and centralized sorting centers, substantially improving recycling. Kigali, Rwanda (pop. ~1.1M) cleans its streets daily and has banned plastic bags, achieving near-total plastic waste collection. While these cases differ from Erbil's context, their shared principle is applicable: comprehensive coverage and enforcement. Experts stress that strategies like source sorting, leak-tight landfills, and waste-to-energy (incineration with energy recovery) are often more impactful than focusing on a single method Zhang et al. (2024) conclude that waste sorting, optimized landfills, and controlled thermal treatment form a coherent strategy aligned with local realities in developing cities (Zhang et al, 2024). The general lesson for Erbil is to assemble an integrated system: improve collection routes and coverage, require household sorting, build adequate processing facilities, and ensure dumps are properly managed.

From these cases, several clear best practices emerge. Cities that achieve high diversion typically enforce source separation (household sorting into at least dry recyclables vs organics) and create recovery facilities (composting plants, material recovery facilities). They couple these with public education and even economic incentives (like reduced fees for sorted recyclables). Erbil's management can draw on such models: for instance, Pune's door-to-door segregation and collection by cooperatives is a blueprint for involving communities. Likewise, Baku's sanitation of its landfill teaches the importance of engineered facilities. And cities like Stockholm or Fukuoka (Japan) suggest that marrying recycling with waste-to-energy is effective – Sweden's case shows that essentially no waste needs to landfill when the right infrastructure existseea.europa.eu. In sum, Erbil can look to both regional peers (e.g. Gulf and Asian cities improving sorting and disposal) and global leaders (Scandinavian and East Asian cities minimizing waste through high-tech processing) to craft a context-appropriate model.

7.2 Lessons for Erbil from Developed Countries

Developed countries offer Erbil advanced techniques and policy tools that can be adapted to local conditions. A key lesson is the emphasis on circular economy and waste minimization. European Union policy, for example, sets legally binding recycling targets (50% by 2020, 60% by 2030) and requires member states to reduce landfill use. As a result, EU cities have implemented many supportive measures. One such measure is pay-as-you-throw (PAYT): billing households by the volume or weight of waste they dispose of. This mechanism strongly incentivizes waste reduction and recycling. The U.S. EPA reports that a small town adopting a PAYT trash-bag system saw its recycling jump over 50% and waste to landfill fall by 35%xc (Skumatz, 2008) . Erbil could adopt a similar "user-pay" approach by introducing prepaid waste bags or waste weight surcharges, which would encourage citizens to sort recyclables and compostable waste at home.

Another lesson is the extended producer responsibility (EPR) approach widely used in the EU, Japan, and beyond. Under EPR, manufacturers and importers of packaging, electronics, tires, etc. must finance or manage take-back and recycling of those products. For instance, Sweden's long-standing EPR laws require companies to pay for collection and recycling of packaging and batteries. This shifts the cost burden off municipalities and induces producers to design for recyclability. While establishing full EPR may be premature for Erbil, the underlying principle – that producers share responsibility – could be introduced gradually. Even voluntary agreements with local industries to minimize packaging or fund local recycling pilots would echo this principle.

Technologically, developed cities heavily use waste-to-energy (WTE) plants and sophisticated recycling facilities. Incineration with energy recovery is common in countries with limited landfill space. As noted, Sweden incinerates about 59% of waste (Country Profile Waste Management – Sweden, 2025), powering district heating networks and virtually eliminating landfilling. Erbil has abundant space, so WTE is less urgent, but other technological transfers are relevant. For example, automated sorting facilities (with conveyors, magnets, optical sorters) dramatically improve recovery of plastics and metals. Composting organics, perhaps in municipal or community-level plants, can reduce waste volume and produce fertilizer. Developed-world standards and engineering designs for landfills, transfer stations, and composters are available through organizations like the World Bank and UNEP; Erbil can apply these standards (e.g. proper liners, leachate controls) to upgrade existing dumpsites. Developed countries also show the importance of data-driven planning and monitoring. Many cities use GIS systems to optimize collection routes (saving fuel) and track waste generation. Erbil's municipality can adopt such tools to improve efficiency. Furthermore, regular waste audits (composition studies) help target efforts: for instance, finding that "food waste is 35% of waste stream" would justify investing in composting. Sharing data and progress publicly, as done in the EU's waste database, also fosters accountability. Finally, enforcement and public engagement are central in advanced contexts. Litter fines, mandatory collection schedules, and bans on certain disposables (e.g. single-use plastics) have worked in many countries. A cultural lesson is that residents of developed cities often view recycling as a civic duty; Achieving this in Erbil will require sustained education campaigns. In summary, Erbil should draw on developed-country strategies by combining regulatory measures (targets, bans, fees) with infrastructure (sorting facilities, engineered disposal) and behavioral programs (education, EPR incentives) (Country Profile Waste Management – Sweden, 2025; Skumatz, 2008). The goal is to create a comprehensive system where waste is first reduced, then reused/recycled as much as possible, and finally treated with minimal environmental impact.

7.3 Potential for Public-Private Partnerships in Waste Management

Public–private partnerships (PPPs) have emerged as a way to bring private investment and expertise into municipal services, including waste management. Globally, many cities use PPPs for parts of their MSW system: for example, waste collection contracts often go to private firms, and large projects (e.g. landfill development or waste-to-energy plants) are financed via concessions. In Erbil itself, much of the waste collection is already carried out by private companies under contract, with the municipality supervising service quality (Aziz et al., 2023). This indicates a de facto PPP model at the collection stage. Formally expanding PPPs could help Erbil modernize its entire system.

In principle, PPPs can mobilize capital and technology that municipalities lack. As Delmon (2015) notes, solid waste requires substantial investment (for landfills or treatment plants) and specialized management, which municipal budgets often cannot coverblogs.worldbank.org. A well-structured PPP could, for instance, build and operate a material recycling facility (MRF) or transfer station. If Erbil ever decides on a waste-to-energy plant, it would likely be through a PPP to secure international finance and engineering. Global experience suggests that integrated waste PPPs (covering multiple stages of the system) can yield economies of scale and better environmental control (Delmon, 2015).

However, waste PPPs have particular challenges. Delmon (2015) cautions that household fee collection is usually weak, so cost-recovery can be poor, making pure revenue-driven projects riskyblogs.worldbank.org. Erbil would need to ensure a steady revenue stream – possibly through municipal payment guarantees, tipping fees at landfills, or energy sales – to attract private partners. The World Bank blogs further emphasize that PPPs in SWM require careful planning: cities must set tariffs or subsidies that make contracts bankable, while maintaining service accountabilityblogs.worldbank.org. For example, many municipalities adopt a hybrid model: the public sector may subsidize core operations (collection), while the private partner earns from recyclables sales or energy (Delmon, 2015).

Erbil's context suggests some immediate PPP opportunities and some constraints. On the opportunity side, given that collection is already privatized, the government could issue long-term service contracts or performance-based agreements to formalize and improve this. Contracts could include targets for diversion (e.g. the contractor must recycle a certain fraction of collected waste). Such contracts should be transparent and monitored, to avoid the "low-bid, low-service" pitfall. For disposal infrastructure, a PPP could finance improvements at the Kani Qirjaka dump (e.g. installing methane capture) or construct a new sanitary landfill. In fact, PPP feasibility studies (e.g. by international donors) might be needed to structure these deals.

A concrete example elsewhere is instructive: Nepal's Biratnagar city implemented a PPP for landfill management and collection, supported by UNDP, which brought foreign expertise into a local waste sector traditionally informal. Similarly, a planned PPP in Baghdad aims to build and operate a waste-to-energy plant (though the project is still under tender) (Delmon, 2015). These cases illustrate that with donor backing and clear contracts, even challenging waste projects can attract private participation.

Yet caution is warranted. Delmon (2015) stresses that without accountability, PPPs can fail; closed dumps may simply shift elsewhere, and companies may prioritize profit over service. In Baku, for instance, the formal improvements coexisted with continued illegal dumping in peri-urban areas, showing that enforcement must accompany any PPP disposal facility (Waste, 2021). Erbil should learn from these experiences by coupling PPP contracts with strong regulatory oversight and public engagement. The UN World Bank partnership guidelines suggest involving communities (e.g. including waste-pickers cooperatives) in PPP planning, to build trust and local capacity.

In summary, PPPs hold promise for Erbil if carefully designed. They could finance new facilities (recycling centers, transfer stations, or WTE), and professionalize operations. However, success will hinge on clear contract terms, realistic cost recovery (possibly with public subsidies for social equity), and robust enforcement. As one review notes, closing illegal dumps or upgrading facilities is ineffective without complementary measures (institutional reforms, education) to change behaviordocuments1.worldbank.org. For Erbil, the potential lies in harnessing private sector efficiency and capital – but only as part of a broader strategy that also strengthens municipal oversight and community involvement in waste management.

Chapter Eight

Conclusion and Recommendations

8.1 Summary of Key Findings

This thesis has provided a comprehensive assessment of municipal solid waste (MSW) management in Erbil City, identifying critical systemic challenges and evaluating global best practices to inform sustainable solutions. The research has revealed that Erbil faces a rapidly growing waste problem, with per capita generation averaging around 1.3 to 1.4 kilograms per day. Organic materials, low-grade plastics, and mixed recyclables dominate the waste stream, yet virtually all waste is collected in a mixed state and transported to the unengineered Kani Qirzhala dump. This site lacks basic environmental safeguards, such as liners, leachate collection, and gas capture, making it a source of groundwater contamination, odour pollution, and greenhouse gas emissions. The institutional landscape is marked by fragmented responsibilities and outdated legislation, with no enforceable framework for source separation, recycling mandates, or environmental accountability.

Infrastructure limitations further exacerbate these problems. The absence of transfer stations, material recovery facilities, and composting plants severely constrains the city's ability to process waste sustainably. The collection system is under-resourced and uneven, with many peripheral areas receiving inadequate service, leading to illegal dumping and open burning. Financial constraints also play a significant role, with limited municipal budgets prioritizing routine collection over long-term infrastructure investment. Public awareness and engagement remain low, with most residents unfamiliar with the principles of waste minimization or the environmental consequences of improper disposal. Nevertheless, the examination of international case studies—from Pune's cooperative recycling to Baku's landfill reform—demonstrates that cities with similar challenges have achieved significant progress through integrated strategies that combine regulatory reform, public-private partnerships, community engagement, and technical innovation.

8.2 Policy and Infrastructure Recommendations

To transition toward a sustainable MSW system, Erbil requires an integrated reform agenda that addresses governance, financing, infrastructure, and public participation. At the policy level, the city should adopt a comprehensive municipal waste management by-law that clearly defines institutional roles and responsibilities, mandates source separation, prohibits open dumping and burning, and establishes diversion targets. Economic instruments such as pay-as-you-throw schemes, differentiated waste collection tariffs, and modest landfill tipping fees can create behavioural incentives while enhancing cost recovery. Erbil should also initiate pilot extended producer responsibility (EPR) schemes, targeting high-priority waste streams such as plastic packaging, to distribute the burden of waste management more equitably between producers and consumers.

From an infrastructure standpoint, Erbil must first improve its waste collection and segregation system. This includes optimizing collection routes using GIS-based tools, investing in a fleet of modern vehicles, and ensuring universal access to service, particularly in underserved informal areas. The introduction of dual-bin systems—one for organic waste and another for recyclables—should be phased in, supported by sustained public awareness campaigns and school-based education programs. Processing infrastructure should be prioritized in tandem. A central material recovery facility (MRF) can help divert recyclables from landfill, while a composting plant will be essential for managing the city's high organic waste fraction. These facilities can be operated under public-private partnerships to leverage technical and financial expertise from the private sector while retaining public oversight.

Regarding final disposal, the transformation of Kani Qirzhala into a modern sanitary landfill—or the development of an entirely new engineered site—is imperative. The new facility should include leachate management systems, methane capture, proper daily cover, and environmental monitoring. Installing a basic gas flaring system would immediately reduce methane emissions, with future potential for energy recovery through biogas-powered generators. These landfill upgrades should be paired with regulatory enforcement to close unauthorized dumps and deter illegal disposal practices. Finally, community engagement must be institutionalized through awareness campaigns, waste-sorting training, and participatory decision-making platforms that involve residents, NGOs, and informal waste workers. By aligning policy and infrastructure with international standards and community needs, Erbil can build a waste management system that is inclusive, resilient, and environmentally sustainable.

8.3 Future Research Directions

While this thesis provides a foundational framework for reforming MSW management in Erbil, several areas require further investigation to support effective implementation. First, more granular data is needed through regular waste characterization studies. These studies should assess seasonal, demographic, and spatial variations in waste composition and generation, enabling tailored solutions for different neighbourhoods. In addition, there is a need for economic feasibility analyses of various treatment technologies—such as composting, anaerobic digestion, and waste-to-energy incineration—under Erbil's specific waste profile and climatic conditions. Comparative life-cycle assessments (LCA) would offer critical insights into the environmental and economic trade-offs between these options.

Socioeconomic research is also essential, particularly in evaluating the potential impacts of proposed financial instruments like PAYT and EPR. Surveys and focus groups should explore public willingness to pay, behavioural drivers of waste sorting, and equity concerns, especially for lower-income households. Moreover, the role of informal waste workers in the existing system remains underexplored. Ethnographic and participatory research can help design policies that integrate informal recyclers into the formal sector in a way that safeguards livelihoods, improves occupational safety, and enhances system efficiency.

In addition, pilot studies involving digital tools for citizen engagement—such as mobile apps for reporting illegal dumping or tracking household sorting behaviour—could reveal new pathways for improving compliance and transparency. Research into climate-resilient landfill design will also become increasingly important as Erbil faces higher temperatures and changing precipitation patterns; engineering studies should address landfill slope stability, leachate volumes, and gas migration under extreme weather conditions. Finally, there is a clear need for research into financing models and public-private partnership (PPP) structures, including case-specific risk-sharing mechanisms, tariff design, and contract monitoring frameworks.

In conclusion, Erbil's waste management system is at a tipping point. While the challenges are significant, so too are the opportunities. With a data-informed, inclusive, and strategically phased approach—supported by evidence-based research—Erbil can create a waste governance model that not only addresses immediate environmental and public health risks but also lays the foundation for long-term circular economy development.

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