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MSc Environmental Engineering

Improving Municipal Solid Waste Management in Essaouira, Morocco

A Diagnostic and Strategic Assessment

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Abstract

Municipal solid waste management (MSWM) is a critical challenge in many low- and middle-income countries, where rapid urbanization, limited institutional capacity, and resource constraints often lead to inefficient, environmentally harmful practices. This thesis investigates how the MSWM system of Essaouira, a mid-sized coastal city in Morocco, can transition from basic collection and disposal toward an integrated, circular model. The research follows a two-phase approach—diagnostic and strategic—combining literature review, fieldwork, stakeholder interviews, and key performance indicator (KPI) analysis tailored to local conditions.

The diagnostic phase revealed systemic inefficiencies across all stages of the MSWM chain. Waste is not separated at the source, public satisfaction with collection and cleanliness services is low, and the so-called "controlled" landfill operates under substandard conditions, closer to an open dump. Recycling and recovery activities are limited to informal and private actors, while legal enforcement and public awareness remain weak. All evaluated KPIs scored between poor and mediocre, underscoring the need for structural reform.

Building on this assessment, the strategic phase proposes a realistic, phased improvement plan. Core recommendations include piloting source separation programs to enable scaling, establishing a central Mechanical–Biological Treatment (MBT) facility at the planned Centre d'Enfouissement et de Valorisation (CEV), and rehabilitating the current landfill through compaction, covering, leachate treatment, and gas capture. Complementary decentralized initiatives—such as composting and micro-recycling hubs—are proposed to strengthen community engagement and employment. Governance reforms, including contractual KPIs, transparent monitoring, the inclusion of informal pickers, and the enforcement of environmental laws form an essential enabling layer.

Together, these measures form a coherent pathway for Essaouira to evolve from reactive waste disposal toward a resilient, inclusive, and circular waste management system aligned with Morocco's national sustainability goals.

Acknowledgments

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Contents

1 Introduction

1.1 Background and Context

Municipal solid waste management (MSWM) is a critical public service that underpins public health, environmental sustainability, and economic development. The world generates approximately 2.01 billion tonnes of municipal solid waste annually, a figure projected to reach 3.40 billion tonnes by 2050 due to rising urbanization and population growth (Kaza et al., 2018). At least one-third of this waste is mismanaged, often through open dumping or burning, resulting in land and water pollution, greenhouse gas emissions, and significant health risks. In developing regions, uncollected waste creates breeding grounds for disease, with an estimated 400,000 to 1 million deaths annually linked to mismanaged waste (Tearfund Consortium, 2019).

These impacts underscore the urgency of improving MSWM systems, especially in low- and middle-income countries where infrastructure development often lags behind urban growth. Many municipalities struggle with inadequate collection, minimal treatment capacity, and limited institutional support. As a result, open dumping and burning remain widespread, and an estimated 2 billion people globally still lack access to basic waste collection services (Tearfund Consortium, 2019). This not only affects local health and ecosystems but also contributes to global problems such as marine litter. Over 8 million tonnes of plastic waste enter the oceans each year, much of it from poorly managed land-based sources in coastal cities.
Tourism further complicates the situation, as tourist destinations face seasonal waste surges, often dominated by single-use plastics and packaging waste. These challenges are especially critical in countries like Morocco, where tourism is a major economic sector but local waste infrastructure often struggles to cope with fluctuating volumes (Wiechert et al., 2025).

Essaouira, a mid-sized coastal city in Morocco's Marrakech–Safi region, exemplifies the challenges mentionned above. Despite recent national efforts to modernize MSWM, many local systems remain underdeveloped. Essaouira's rapid growth, tourism intensity, and constrained municipal resources have resulted in inefficient waste collection, reliance on poorly managed landfilling, and limited recycling or treatment initiatives. Addressing these challenges is crucial not only for environmental protection, but also for safeguarding the city's public health, tourism appeal, and long-term sustainability.

1.2 Problem Statement

Prior to this study, no comprehensive evaluation had been conducted on the performance of MSWM in Essaouira. While Morocco has made national efforts to modernize its waste sector, little was known about how these ambitions have translated at the local level. In the absence of reliable data, performance indicators, or formal municipal planning, it remained unclear whether the existing system was adequate, what its key inefficiencies might be, and what practical steps could be taken to improve it. This lack of structured assessment limited the ability of local decision-makers to prioritize interventions or align with broader sustainability goals.

1.3 Research Objectives and Questions

The main objective of this thesis is to evaluate the current state of MSWM in Essaouira and develop a realistic, context-sensitive plan for its improvement. To guide this research, one main research question (RQ) and five sub-questions (SQs) were formulated:

Main Research Question:

> *How can the current municipal solid waste management strategy in the municipality of Essaouira, Morocco, be improved?*

Sub-Questions:

1. What are the key inefficiencies in Essaouira's current waste management system?
2. What is the impact of highly touristic seasons on MSWM?
3. What key performance indicators (KPIs) can be used to measure the success of the waste management practices?
4. How does Essaouira's MSWM system compare to international best practices?
5. What improvements can be implemented to enhance MSWM in Essaouira?

1.4 Thesis Structure

This thesis is structured in six chapters and follows a two-phase approach: a diagnostic phase aimed at assessing the performance of the MSWM system in Essaouira, and a strategic phase dedicated to proposing a plan for its improvement.

Chapter 1 here introduces the topic, outlines the background and problem statement, and presents the research objectives and questions guiding the study.

Chapter 2 presents the literature review. It first defines key concepts in MSWM and reviews technical elements such as waste collection, treatment, and disposal. It then examines the current state of MSWM in Morocco, with a focus on the legal framework and national modernization efforts. The case of Essaouira is introduced more deeply, with a first analysis of the available studies on the MSWM of the city. Key performance indicators (KPIs) are analyzed and a set of KPI is defined for the diagnostic of Essaouira's MSWM. Finally, best MSWM practices in developing countries are investigated for further use in the strategic phase.

Chapter 3 explains the research design and methods. It details the qualitative and quantitative approaches used in the fieldwork, including semi-structured interviews, site visits, and document analysis, as well as the use of KPIs to evaluate system efficiency.

Chapter 4 constitutes the diagnostic phase. It analyzes Essaouira's current waste generation, collection and cleaning services, treatment pathways, landfill conditions, and stakeholder engagement. This chapter also includes a performance assessment based on selected KPIs and answers the first three sub-questions of the research.

Chapter 5 presents the strategic phase. Based on the diagnostic findings and international best practices, it proposes a series of locally adapted recommendations to improve Essaouira's MSWM system. These include short-, medium-, and long-term interventions focused on collection and cleaning, source separation, decentralized treatment, landfill rehabilitation, and legal enforcement and public engagement. This chapter answers the final two sub-questions and addresses the main research question.

Chapter 8 concludes the thesis by summarizing the key findings, answering the main research question, and reflecting on the study's limitations and potential avenues for future work.

1.5 Relevance of the Study

This study contributes both academically and practically to the field of MSWM in developing contexts. From a practical perspective, it provides the first structured assessment of Essaouira's waste management system, grounded in fieldwork, stakeholder interviews, and KPIs. The findings can support local authorities in identifying priorities, designing targeted interventions, and aligning with Morocco's national waste management policies.

Given the growing pressure of urbanization and tourism in mid-sized coastal cities, the case of Essaouira offers insights that may be applicable to other municipalities in Morocco and across the MENA region. Furthermore, the thesis proposes context-sensitive strategies based on international best practices, adapted to local financial and institutional constraints.
From an academic perspective, the research contributes to the limited body of literature on MSWM performance assessments in secondary Moroccan cities. By integrating qualitative and quantitative methods, the study also provides a replicable framework for diagnosing waste systems and formulating realistic improvement plans under data-scarce conditions.

2 Literature Review

This literature review provides the foundation for both the diagnostic and strategic phases of the thesis. First, it introduces the key concepts and operational pillars of modern MSWM, including the waste hierarchy, circular economy principles, and integrated management frameworks. It then examines the implementation and evolution of MSWM in Morocco, focusing on national programs such as the PNDM and PNVDM, as well as the legal instruments for waste governance. A specific subsection is dedicated to the case of Essaouira, synthesizing available studies on the city's waste composition, infrastructure, and collection practices within its unique coastal and touristic context.

In the second part of the review, the focus shifts to international best practices and enabling policies for effective MSWM in developing country contexts. Drawing on global case studies, this section identifies successful models of MSWM. It also reviews regulatory mechanisms—such as extended producer responsibility (EPR), incentive-based systems, and multilevel governance frameworks—that have been shown to improve environmental performance and service equity. These insights will inform the strategic phase of the thesis, serving as a comparative lens for proposing context-appropriate interventions to improve MSWM in Essaouira.

2.1 Municipal Solid Waste Management

Municipal solid waste (MSW) refers to the everyday solid wastes generated by urban populations from households, commerce, institutions, and similar sources, which municipalities are responsible for managing. It includes items like food scraps, product packaging, yard trimmings, paper, plastics, glass, and other common discards (UN-Habitat, 2025; EPA, 2015). It may also include waste from municipal services (street sweepings, park waste) and bulky items (old furniture, appliances) if collected by the city. Notably, MSW excludes industrial process wastes, construction and demolition debris, and hazardous wastes, which require different handling. The United Nations defines MSW as waste generated from households and similar waste from commerce, small businesses, and municipal activities, stressing that it comprises the solid waste stream that local authorities typically collect and treat (UN-Habitat, 2025).
As cities grow, managing this diverse waste stream safely and efficiently becomes a core urban service. Effective MSW management (MSWM) is essential to prevent the harmful impacts that uncollected or improperly disposed waste can have on public health and the environment, such as spreading deadly diseases, contaminating water and soil, clogging drainage (and causing floods), and blighting communities (UNEP, 2025; WHO, 2024). Overall, MSWM thus covers the collection, transport, recovery, and disposal of everyday solid waste in a way that should protect human health and promote environmental quality.

2.1.1 Guiding concepts

Modern MSWM systems are based on fundamentals principles and concepts that emphasize sustainability and resource conservation. A central guiding framework is the **waste management hierarchy** (see Figure 1), which ranks waste management practices in order of desirability, from the most preferred options to the least one, to encourage outcomes that minimize waste and its impacts. At the top of the hierarchy is waste prevention or reduction– avoiding the generation of waste in the first place – followed by the reuse of products and materials, then recycling (and composting) to recover materials, then energy recovery (e.g. through incineration with energy capture or biogas production), and lastly disposal as the least preferred option (WHO, 2024). This hierarchy is adopted in policies such as the EU Waste Framework Directive (European Commission, 2025b).
Alongside the hierarchy, the concept of circular economy has also become very influential. In a circular economy, one moves away from the traditional "take-make-dispose" linear model towards a circular one where materials are kept in use for as long as possible. It prioritizes reuse, repairing, refurbishment, and recycling of products and materials, thereby conserving resources and reducing overall waste generation (UNEPFI, 2025); WHO 2024).
Circular economy principles in MSWM can significantly reduce the amount of waste requiring final disposal in landfills and also reduce the extraction of new raw materials. For instance, incorporating recycled materials into production and designing products for easier reuse or recycling can close the loop of material flows.
Overall, the waste hierarchy and circular economy concept both aim at waste minimization and resource recovery, aligning MSWM with broader sustainability goals.

Figure 1: Waste Hierarchy (European Commission, 2025b).

Several other basic principles reinforce proper MSWM practices, as introduced in the Waste Framework Directive (European Commission, 2025b). One of them is the "polluter pays" principle, which holds that the costs of waste management should be borne by the people who generate the waste, internalizing environmental costs. This principle often underlies financing mechanisms like waste collection fees or landfill taxes, and it also connects to the Extended Producer Responsibility (EPR). EPR programs make manufacturers responsible for the end-of-life management of their products (for example, electronics or packaging), pushing them to design more recyclable products and fund recycling systems (European Commission, 2025b). Another important concept is Integrated Solid Waste Management (ISWM), which promotes a strategic, life-cycle approach to manage all types of waste. ISWM addresses the entire waste stream (from generation to final disposal) in a coordinated and sustainable way. It emphasizes maximizing resource efficiency and involving multiple stakeholders, from local governments to businesses, service providers, and citizens. It also considers technical, economic, social, and environmental factors to develop waste management systems (Memon, 2011).

2.1.2 Waste collection

In terms of collection methods, MSWM involves organized collection services to collect waste from where it is generated and transport it to treatment or disposal sites. Collection systems can include door-to-door pickup, collection from bins, and collection from communal containers at designated points. The efficiency and coverage of waste collection are fundamental to preserve public health. In many low-income countries, the official MSWM is often supplemented by informal waste collectors or community-based systems (Dias, 2016). They collect recyclables from people, bins, or landfills in order to sell them and make a living out of it.

2.1.3 Waste treatment

After collection, treatment and disposal methods for MSW can take several forms, each with their own role in the waste hierarchy. Recycling for example, is a key treatment method in MSWM, as it allows materials to be collected and processed for reuse rather than being sent to landfills. It plays an important role in reducing environmental impacts and saving resources. However, recycling practices vary depending on the type of material. High-value materials like metals are often recycled because they are profitable, while low-value materials such as mixed plastics are more costly and complex to process. As a result, recycling often depends not only on environmental awareness but also on economic incentives and government regulations. Therefore, the success of recycling often relies on collaboration between governments, businesses, and citizens (Oberoi, 2020).

Organic waste cannot be recycled per se, as it does not undergo the same material recovery processes as plastics, metals, or paper. However, it can be effectively treated through biological methods. Two of the primary biological treatment methods for organic waste are composting and anaerobic digestion (Polprasert and Koottatep, 2017). Composting is an aerobic process where microorganisms decompose organic matter, such as food scraps and garden waste, into a nutrient-rich soil amendment. This method not only reduces the volume of waste sent to landfills but also produces compost that can enhance soil fertility. On the other hand, anaerobic digestion involves the breakdown of organic materials in the absence of oxygen, resulting in the production of biogas and digestate, which can be used as a fertilizer. Both methods contribute to sustainable waste management by recovering valuable resources from organic waste streams.

When waste cannot be recycled or biologically treated, another way to recover some of its value is to burn it via waste-to-energy (WtE) technologies. WtE technologies, particularly incineration, serve as a critical treatment option for MSW by reducing the volume of waste and generating renewable energy. Modern WtE facilities integrate advanced combustion systems and air pollution controls to ensure environmental compliance. Incineration can recover energy in the form of heat and electricity, which makes it a viable solution, especially where landfill space is limited. Today, WtE plays an important role in waste management systems, particularly in Europe, East Asia, and parts of North America, offering an alternative to landfilling for non-recyclable waste fractions while contributing to energy diversification (Makarichi et al., 2018).

2.1.4 Waste Disposal

As a last resort, when waste cannot be recovered at all, it is disposed of in landfills. This type of waste management strategy remains a widespread method for the final disposal of MSW, especially in regions lacking advanced treatment infrastructure (Agamuthu, 2013). The evolution of landfilling practices is commonly described through two main types: uncontrolled landfills, and engineered or controlled/sanitary landfills. Uncontrolled landfills, or open dumps, are the most basic and hazardous form of waste disposal. Waste is deposited directly onto the ground without any engineering, regulation, or environmental protection. There is no compaction, covering, or drainage system, and access is typically unrestricted. These sites often attract informal waste pickers, who search for recyclable materials in unsafe conditions. Animals, particularly livestock, may feed from the waste, increasing health risks. Open dumps cause serious environmental impacts, including groundwater contamination, air pollution from open burning, and the spread of disease vectors (Townsend et al., 2015). Unfortunately, this type of landfilling remains one of the most common form of disposal in developing countries such as in Africa or Asia (Zhang et al., 2024).

In contrast, engineered landfills offer massive improvement. They include regular compaction, periodic soil covering, and fencing or site supervision. These landfills are designed for environmental safety, featuring impermeable liners, leachate collection and treatment, and gas capture systems. They also have runoff controls and regular monitoring of groundwater and emissions. They are operated under strict regulations and therefore represent the safest way of waste disposal (Townsend et al., 2015).

2.2 MSWM in Morocco

Before the implementation of major reforms, Morocco faced serious challenges in its MSWM system. In 2015, the country generated approximately 5.3 million tons of urban waste per year, equivalent to 0.76 kg per capita per day, while rural areas produced about 1.6 million tons annually, or 0.3 kg/capita/day (El Maguiri et al., 2017). Waste collection in urban areas was marked by frequent container overflows, due to undersized or insufficient bin infrastructure, and irregular collection schedules. Collection routes were often not respected, and financial oversight was weak. Moreover, prior to 2008, the majority of collected waste was dumped in uncontrolled municipal landfills, with an estimated 300 such sites across the country (El Maguiri et al., 2017). These sites were usually located on the outskirts of cities, lacked environmental assessments, and suffered from poor conditions: absence of fencing or road access, open burning, informal scavenging, presence of hazardous and medical waste, and livestock feeding directly on the waste. This led to serious environmental and health risks, including the release of toxic fumes and the contamination of food chains and nearby communities (El Maguiri et al., 2017).

In 2008, the Moroccan government launched the National Municipal Solid Waste Management Program (Programme National des Déchets Ménagers, PNDM), a 15-year plan, designed with the help of the World Bank, which aimed at improving municipal solid waste management nationwide. This program was designed to operationalize the goals of Law 28-00 on waste management and disposal (see Section 2.4), which had been adopted two years earlier to formalize and structure the sector at both national and municipal levels.
The program had several ambitious targets:

- Ensuring the collection and cleaning of municipal solid waste to achieve 90% collection coverage in urban areas by 2020.
- Ensuring 100% of urban waste is disposed of in controlled landfills.
- Rehabilitating or closing 100% of non-controlled landfills (300 sites).

It also promoted the integration of recycling and waste recovery as key components of the system and aimed to achieve a 20% recycling rate by 2020. To reach these goals, the program introduced a performance-based funding mechanism, providing financial support from the central government to municipalities based on transparent eligibility criteria. The PNDM also encouraged private sector participation through delegated management contracts aimed to improve institutional capacity via training, planning tools, and standardized contract models. Another important point of the program was social inclusion, which consisted of different pilot projects to integrate informal waste pickers into formal cooperatives. The goal was to integrate them into the formal MSWM system by improving their working conditions, providing them with legal recognition, and increasing their participation through training, equipment provision, and the creation of sustainable income opportunities. The total cost of the PNDM was estimated at around 40 billion Moroccan dirhams and distributed as follows (Ministère de la Transition Énergétique et du Développement Durable, 2015):

- Collection and cleaning: 72%
- Construction and operation of controlled landfills: 14.6%
- Rehabilitation and closure of illegal dumps: 6.3%
- Studies, monitoring, and control: 3.5%
- Sorting, recycling, and recovery: 1.8%
- Communication, awareness, and training: 1.8%

2.2.1 Evaluating the impact

In 2022, the collection rate achieved 96%, exceeding the 90% target set by the PNDM and more than doubling the baseline of 44% collection rate before the reform efforts began (World Bank, 2022). However, waste separation at the source remained very limited and waste hierarchy principles (reduce, reuse, recycle) were not implemented.

By 2020, 26 controlled landfills were constructed compared to only 6 before the program, one of which is operational in Essaouira. Additionally, 24 new landfill projects were presented for 2021. However, it is very likely that they will not take place, according to the World Bank (2022), and the total amount of controlled landfills therefore remains far from the 80 landfills planned for the end of 2020. These landfills totaled a disposal rate of around 63% by 2022, compared to 10% prior to 2008 (GIZ and SWEEP-Net, 2014; World Bank, 2022), which is a strong evolution, although not meeting the initial target. However, the very high organic content of the waste generates high quantities of leachate that are hard to process and dispose of due to the limited capacity of some landfills (Climate Chance Observatory, 2020). As for the closure and rehabilitation of illegal dumps (300 estimated), only 60 of them were actually handled.

Concerning the recycling, only 8–10% of waste was being recycled by 2020, falling significantly short of the 20% recycling target originally set by the PNDM for that year (Climate Chance Observatory, 2020; World Bank, 2022). This is due to the lack of source separation, weak citizen engagement, and limited valorization of recyclable materials (World Bank, 2022). Within these recycling rates, most of the recycled materials are metals (46%), followed by plastics (25%), and paper and cardboard (20%) (SEDD, 2019).
Additionally, although eco-tax revenues were introduced on plastic packaging producers and importers (as a sort of "polluter pays" principle) to support recycling infrastructure, only a fraction of the funds were actually utilized due to restrictive eligibility conditions and insufficient local capacity (World Bank, 2022). Informal waste pickers, who play a central role in Morocco's recycling value chain, are responsible for collecting up to 66% of recyclable plastic waste in the country (Boujrouf, 2020). However, they remained largely excluded from formal systems. While pilot projects such as the cooperative in Meknes or the Oum Azza sorting center in Rabat showed promising results, they remained isolated cases rather than national standards (Climate Chance Observatory, 2020; World Bank, 2022).

Overall, while Law 28-00 and the PNDM have undeniably helped structure and modernize Morocco's municipal solid waste sector, its implementation has been uneven. Key goals in recycling, landfill coverage, and informal sector integration are only partially met, and funding gaps remain. Therefore, new plans are required in order to continue the innovation and push towards a more sustainable MSWM system.

In response to these persistent challenges, the Moroccan government launched in 2023 the National Municipal Waste Management and Valorization Program (Programme National de Valorisation des Déchets Ménagers, PNVDM). This new program builds on the PNDM and insists on the importance of environmentally sustainable waste practices, such as reducing landfilling, improving waste recovery, and integrating circular economy principles. In November 2024, the World Bank approved a US$250 million program, which aims to support the sector's financial and environmental performances. Their goal is to provide technical assistance and investment support to again, modernize landfill operations, close uncontrolled dumpsites, enhance revenue generation models, and promote emissions tracking aligned with Morocco's commitments under the Paris Agreement (EIE Maroc, 2024; World Bank, 2024a).

To frame these operational efforts within a long-term vision, Morocco also introduced the Waste Reduction and Recovery National Strategy (Stratégie Nationale de Réduction et de Valorisation des Déchets, SNRVD) in 2019. This national strategy, developed by the State Secretary in charge of Sustainable Development (SEDD) with support from GIZ, seeks to transition the country from a linear to a circular economy. The SNRVD targets a 70% recycling rate for plastics and 80% for metals and paper by 2030, and includes 30 concrete actions structured around eight strategic axes, ranging from legal reforms to institutional coordination and citizen awareness (SEDD, 2019). It also emphasizes the need to integrate informal actors, strengthen eco-design practices, and reduce Morocco's dependence on landfilling by expanding valorization pathways (SEDD, 2019). As such, the SNRVD provides another backbone to the operational mechanisms of the PNDM and PNVDM.

2.3 MSWM in Essaouira

Despite the increasing importance of waste management in Essaouira, as explained in the introduction, there is still very limited literature focused specifically on this city and province. Most studies are conducted at the national level and either generalize across urban centers or focus on larger cities such as Casablanca, Rabat, or Marrakech, while smaller coastal cities like Essaouira remain underrepresented.

The few available studies, such as those by the DGCL (2012), Chiguer et al. (2016), Zalaghi et al. (2019), and Wiechert et al. (2025), offer valuable insights. However, these analyses focus on isolated aspects of the municipal solid waste management (MSWM) system—such as tourism-related pressures, waste composition, or landfill diagnostics—rather than providing a holistic diagnosis of the city's overall waste management framework. We know from these studies that MSWM in Essaouira consists primarily of waste collection without any separation at the source, followed by direct transport to a controlled landfill. These studies will nevertheless be reviewed in the following sections.

2.3.1 Waste characterization

The study by the DGCL 2012 focuses on waste composition and gathers several household and similar waste characterization studies performed for different cities in Morocco, including Essaouira. The goal of a waste characterization study is to identify the composition of certain waste deposits in order to better understand the quantities and types of materials generated. This can be used to evaluate their potential for recycling or treatment, and support the planning of more efficient and sustainable waste management strategies.

In the case of Essaouira, the study was conducted over three separate campaigns between 2004 and 2006 and followed a standardized methodology based on the MODECOM protocol. Waste samples were collected from various socio-economic zones across the city and manually sorted into defined categories. The results from Figure 2 show that fermentable organic matter represented the largest share of the waste stream sampled, averaging around 61% of the wet mass, with around 55% in April and 67% during the highly touristic season. Plastics accounted for approximately 9% (with a slight increase during the touristic season), paper and cardboard around 5%, and textiles around 5% as well, while metals and glass only presented 1% and 2% of the total waste, respectively. Fines (particles <20 mm) ranged between 3% and 14%, and hazardous waste made up about 2% of the total mass. The composition of waste between socio-economic categories was not significantly different, except for higher income neighbourhoods which tended to have more paper, cardboard, and sanitary textile waste.

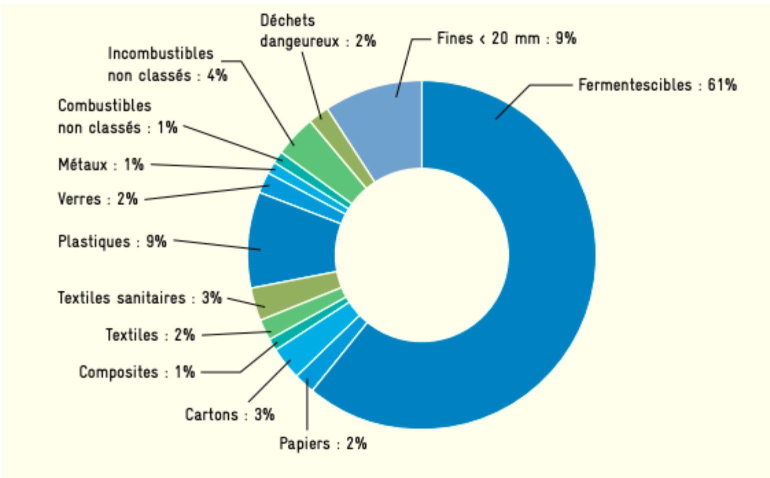


Figure 2: Average composition of household waste in 2004 in Essaouira (DGCL, 2012)

Chiguer et al. (2016) provide further insight into the composition and evolution of municipal solid waste in Essaouira. Their study, initially focusing on leachate quality, includes data on the quantities and types of waste received at Essaouira's controlled landfill. Between 2001 and 2014, the quantity of waste landfilled increased from 14.5 to 26 thousand tons per year, with a daily average of 65 tons over that period. This growth is attributed to both demographic expansion and the significant growth of tourism (see Figure 3).

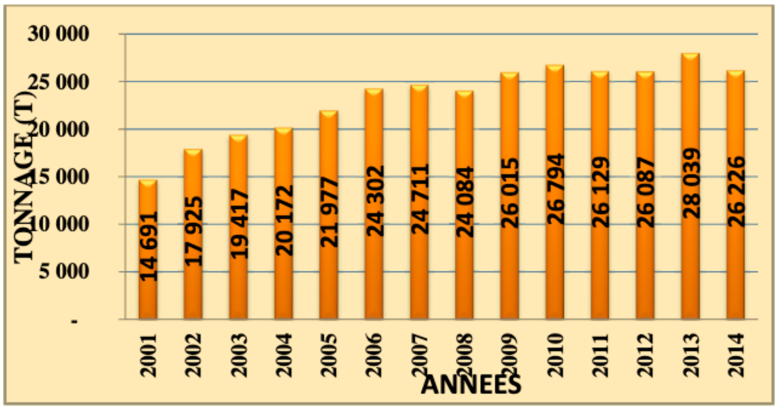


Figure 3: Evolution of buried waste tonnage at Essaouira's landfill between 2001 and 2014 (Chiguer et al., 2016)

In 2014, a detailed characterization study revealed that the city's solid waste stream was dominated by organic matter, which accounted for approximately 70% of total wet weight. The waste also contained about 9% plastics and non-negligible quantities of hazardous waste (2%), coming from medical-hospital waste. These numbers are in accordance with previous findings from the DGCL 2012.

Overall, these findings highlight the predominance of biodegradable waste in Essaouira's municipal waste stream, reinforcing the potential for organic waste treatment strategies such as composting. At the same time, the presence of recyclable dry fractions like plastic and paper shows that there are opportunities for material recovery, although no structured separation or valorization system currently exists. They however also show the presence of hazardous waste, which is not compliant with the Class 1 status of the landfill, and significantly complicates its treatment processes and environmental risk management.

2.3.2 Essaouira's Landfill

Concerning waste treatment and disposal in Essaouira, not much is currently being done. Only one controlled landfill is operational, serving as the final destination for all municipal solid waste generated in the region. It was inaugurated in 2001, becoming the first engineered landfill in Morocco. Initially covering an area of 12.6 hectares, it was later extended to 29 hectares, including 5.58 hectares dedicated to waste burial, in order to meet the region's growing waste disposal needs (Chiguer et al., 2016; Zalaghi et al., 2019).
It is classified as a Class 1 landfill, designed to receive non-hazardous municipal waste. The infrastructure includes lined waste cells, a leachate collection system, a storage and evaporation basin, and internal roadways. Waste is deposited into cells that are equipped with a geomembrane liner and gravel drainage layer, which direct leachate toward the evaporation basin, with an estimated capacity of 17,000 m^3. The landfill's total lifespan was estimated between 15 and 18 years, meaning it has now likely reached or exceeded its designed capacity since its extension and upgrade plan in 2006, which projected an operational duration of only 10 to 12 more years (Chiguer et al., 2016). However, Zalaghi et al. (2019) note that the site is designed to enable the addition of new dumpsters, which could extend the landfill's lifespan to over 50 years.

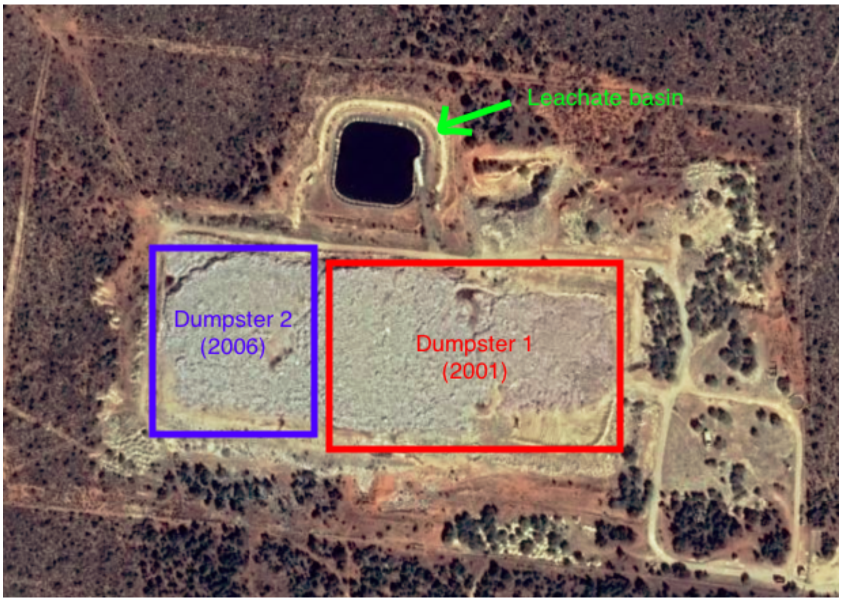


Figure 4: Sky view of Essaouira landfill in 2016, based on (Chiguer et al., 2016)

Chiguer et al. (2016) also studied the physico-chemical properties of the landfill's leachate over four years. Their results showed very high levels of persistent pollution. The chemical oxygen demand (COD) of the leachate ranged from 6,106 to 13,939 mg/L, with an average of 10,361 mgO_2/L, around 20 times the discharge limit of 500 mgO_2/L. The biochemical oxygen demand (BOD_5) was much lower, averaging 632 mg/L. This led to a low BOD_5/COD ratio (≈0.06), which is typical of old, poorly biodegradable leachate. In other words, the leachate is stable and highly polluted with non-biodegradable organic matter, which is difficult to treat with biological processes alone.
Moreover, electrical conductivity—an indicator of mineral pollution—averaged 39,983 µS/cm, far above the acceptable discharge threshold of 2,700 µS/cm. This is partly explained by marine-origin waste from the port of Essaouira. Heavy metal contamination was also observed, with chromium levels reaching 1,720 µg/L, exceeding Moroccan standards by over eight times. While lead and cadmium concentrations were within legal thresholds, the presence of sanitary and medical waste in the landfill raises serious concerns about long-term contamination and occupational health risks for informal waste pickers.
Overall, the study demonstrates that while Essaouira's landfill may meet the technical criteria of a "controlled" site, its environmental performance is inadequate. The authors conclude: "the leachate from the Essaouira landfill is an old, stabilized leachate characterized by low and difficult biodegradability and a very complex organic load."

Zalaghi et al. (2019) complement these findings by focusing on the evolution of waste behavior within the Essaouira landfill. Their study is particularly relevant as it analyzes in situ temperature and moisture variations in buried municipal solid waste to assess the site's biodegradation potential. Over a two-year period, they observed that moisture content increases with depth, especially during the rainy season—rising from 57% at 1m to 81% at 3m. Simultaneously, waste temperatures ranged from 32°C to 45°C. These conditions are considered favorable for thermophilic microbial activity and biogas production.
The study highlights that moisture content is the most influential parameter in the degradation process—more so than temperature. This emphasizes the critical role of water availability in semi-arid regions like Essaouira. According to the authors, a minimum moisture content of 20% is required to maintain microbial degradation, particularly for biogas generation. However, they also note operational limitations, such as the lack of compaction equipment and inconsistent drying practices, which limit the landfill's valorization potential.

2.3.3 Tourism-linked waste strategy

Finally, one of the most recent studies on waste management in Essaouira is the work by Wiechert et al. (2025), published as part of the *Tourism Marine Litter (TouMaLi)* project, which explored the link between tourism and waste management in three coastal cities across the MENA region, including Essaouira. The study's primary objective is to investigate how the tourism sector, particularly hotels, can contribute more proactively to improving local waste infrastructure.
In Essaouira, the authors assessed waste practices in 19 hotels through field visits, questionnaires, and expert interviews. Their results showed that the majority of hotels lacked proper infrastructure to separate their waste, with 87% reporting insufficient bin availability and nearly 70% not practicing any form of waste separation.

The study highlighted the absence of regular waste monitoring and revealed that most establishments rely on municipal collection services without any structured recycling system. Interestingly, the study also found that, in contrast to many other Moroccan cities, the informal sector plays only a marginal role in hotel waste management in Essaouira. The company responsible for collecting the waste is ARMA, a private firm contracted by the municipality since early 2024, but no formal recovery system or separation scheme is currently in place at the municipal level.

To address these issues, the study proposes an "Extended Sector Responsibility" (ESR) model, where the tourism sector, local authorities, and waste service providers would co-manage a dedicated Waste Recovery Centre. This facility would handle the sorting and valorization of recyclable and organic waste and offer incentives for informal sector involvement. Funding would come from Extended Producer Responsibility (EPR) schemes or tourism-related taxes. A more detailed scheme of this proposal is presented in Figure 5.
In Essaouira, however, while land has already been allocated by the municipality, stakeholder coordination is still lacking. Overall, the proposal represents a highly promising step forward, as it already addresses waste generated by the tourism and hospitality sector, a key contributor to Essaouira's local economy. By focusing on this specific stream, the initiative helps reduce the burden on the municipal system and demonstrates the potential of collaborative, sector-based solutions. However, to achieve a truly comprehensive waste management strategy, further efforts are needed to tackle the household waste stream, which represents the majority of municipal solid waste in Essaouira.

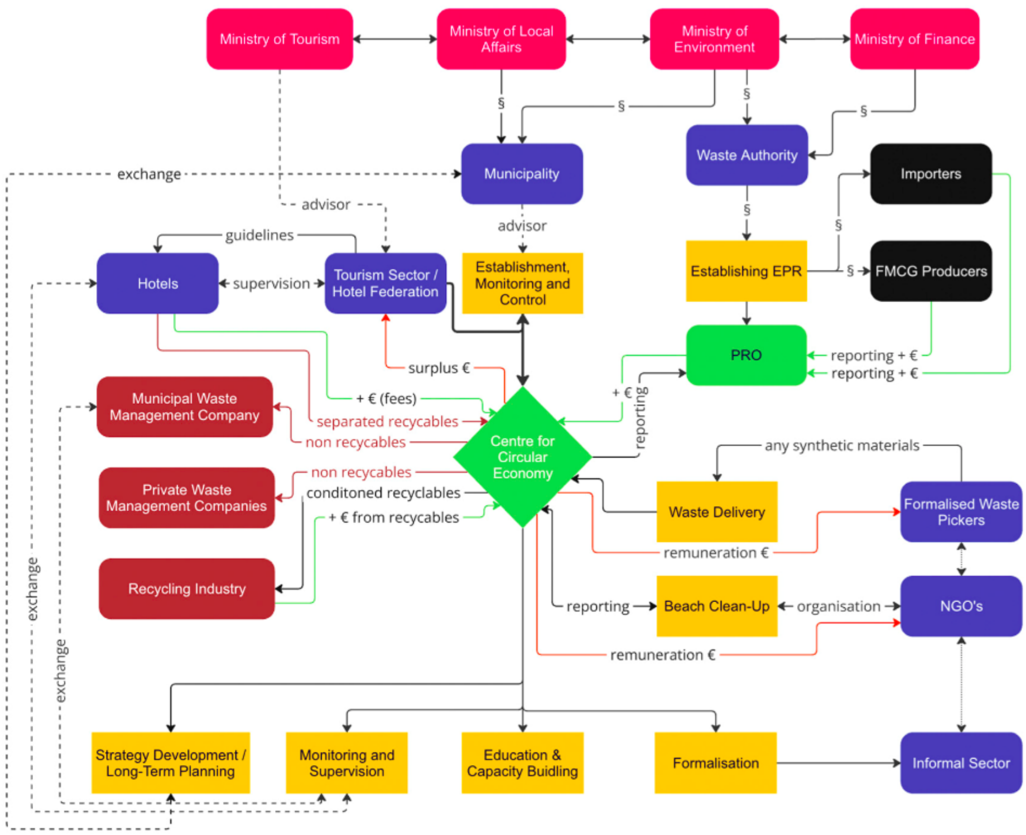


Figure 5: Theoretical Extended Sector Responsibility scheme (Wiechert et al., 2025)

2.4 Morocco's Legal Framework

Over the last two decades, Morocco has emerged as a regional leader in environmental policy, increasingly aligning its national strategies with global sustainability goals. The country demonstrated its commitment to environmentally sound waste management by ratifying key international treaties such as the Protocol on the Prevention of Pollution of the Mediterranean Sea (1983), the Montreal Protocol (1992), the Basel Convention (1995), the Stockholm Convention (2004), the Rotterdam Convention (2002), the Kyoto Protocol (2002), and the Minamata Convention (2017). Regionally, Morocco also adheres to the Bamako Convention and the Barcelona Convention, which support its role in both African and Mediterranean environmental cooperation. Morocco also collaborates closely with the European Union through initiatives like the EU–Morocco Green Partnership and the European Neighbourhood Policy, which provide support for advancing sustainable waste management and circular economy practices.

These legal commitments are backed by ambitious national programs and reforms. Their goal is to modernize waste management, promote recycling, reduce pollution, and overall mitigate climate change. Notably, Morocco is one of the few African countries to have submit a Nationally Determined Contribution (NDC) under the Paris Agreement, with clear targets for emissions reduction, including those related to the waste sector (NDC Partnership, 2021). The implementation of the National Charter for Environment and Sustainable Development (Law 99-12), the eco-tax on plastic packaging, and the ban on single-use plastic bags (Law 77-15) further demonstrate their motivation to integrate environmental concerns into public policy. Within this broader context, the adoption of Law 28-00 on Solid Waste Management in 2006 also marked a crucial legal milestone that shifted municipal solid waste governance from informal and unregulated practices toward a more structured, environmentally sound, and socially inclusive system.

2.4.1 Foundation for Modern Waste Management in Morocco

The "Law No. 28-00 on Waste Management and Disposal" (2006) was a turning point for MSWM in Morocco. It was introduced as a result to the growing concerns about environmental degradation, public health risks, and the inefficiency of waste services, which consisted mostly of informal and unregulated practices. This law laid the foundation to :

- Define different types of waste;
- Clarify the responsibility of local and national authorities;
- Set technical and environmental standards for collection, transport, treatment, and disposal;
- Encourage public awareness and environmental protection;
- Require municipalities to prepare waste management master plans.

It also introduced important environmental principles such as the "polluter pays" and the need for environmental impact assessments (EIAs) for MSW facilities. The goal was to shift the focus of MSWM from basic cleanliness to a more environmentally sound waste management system. This law thus became the primary legal reference for municipal solid waste governance across Moroccan cities, including Essaouira.

2.4.2 Complementary Legal Framework

In addition to Law 28-00, several other legal instruments reinforce Morocco's commitment to sustainable waste management. These include laws on local governance, environmental protection, and coastal zone management, all of which influence how waste is handled at the municipal level.

The "Organic Law No. 113-14 on Local Governments and Communes" (2015) defines the organization and responsibilities of municipalities as the basic administrative unit in Morocco's governance system. It puts municipalities in charge of managing local services, including solid waste collection, street cleaning, and landfill oversight. According to this law, municipalities are responsible for planning, financing, and overseeing local waste service. It also requires them to promote citizen participation and transparency, increasing public awareness. Communes are required to prepare different development plans, including a waste management master plan aligned with Law 28-00.

The "Framework Law No. 99-12 on the National Charter for Environment and Sustainable Development" (2014) calls for integrating sustainability principles into all public policies, including waste management. It requires the integration of environmental criteria into urban planning and public procurement such as waste infrastructure. It also promotes the adoption of "polluter pays" principle and the concept of Extended Producer Responsibility

(EPR). Law 99-12 encourages authorities to support recycling, waste reduction, and circular economy principles, and it introduces the requirement for Environmental Impact Assessments (EIAs) for certain projects.

Law 77-15 (2015) consists of a ban on single-use plastic bags. It forbids the manufacture, import, sale, and distribution of plastic bags made from polyethylene. This law aims to reduce plastic pollution in landfills, public spaces, and natural environments, and encourages the shift to biodegradable or reusable alternatives.

Finally, the "Law No. 81-12 on the Protection and Development of the Coastline" (2015) focuses on coastal zone management, which has implications for solid waste governance, especially in coastal regions like Essaouira. It establishes a 100-meter coastal protection zone where most development, including waste dumping, is restricted. Municipalities are required to ensure that waste does not pollute the coastline, beaches, or marine environments. Overall, this law reinforces the need for proper waste containment and disposal systems in coastal communes and enhances pressure on local governments to control informal or illegal disposal activities that threaten marine ecosystems.

2.5 KPI for MSWM evaluation

Measuring performance is crucial for a good municipal solid waste management. Key performance indicators (KPIs) are tools which help evaluating how well different components of an MSWM system are functioning and identifying gaps for improvement. For over 30 years, waste managers and researchers have used KPIs to measure efficiency, service quality, environmental protection, cost-effectiveness, and other outcomes in MSWM (Cervantes et al., 2018). By transforming complex waste management processes into measurable indicators, KPIs enable data-driven decision-making and help shift management from reactive emergency responses, as it often is the case in developing countries, to a better planned approach (AlHumid et al., 2019). However, developing a standardized or universal set of MSWM KPIs is complicated because of the difference in contexts of studies and limited data (Cervantes et al., 2018). Cervantes et al. (2018) divided MSWM KPIs into five different categories, including technical, environmental, economic, social, and public health. This helps understanding the different aspects of waste management. For our analysis, we will continue with this categorization, however combining social and public health, and adding governance/institutional KPIs, and review for each, the different indicators found in literature. A summary of the main studies used for this literature review, along with their contextual focus and KPI categories, is provided in Table 1.
Section 2.5.1 to 2.5.5 review the different KPIs used in these studies, while Section 2.5.6 defines the ones which will be used in this thesis.

Table 1: Summary of KPI Studies in MSWM

Study	**Country/Context**	**Main KPI Categories**	**Notable Features**
Turcott Cervantes et al. (2018)	Multiple countries, global review	Technical, Environmental, Economic, Social, Health	Categorized 377 indicators; commonality statistics; global benchmarking
Singh et al. (2025)	India (Nagpur), developing urban context	Technical	Framework of 20 detailed technical indicators
AlHumid et al. (2019)	Saudi Arabia, Gulf context	Technical, Environmental, Economic, Governance	Hierarchical framework for Gulf MSWM systems
Sanjeevi & Shahabudeen (2015)	India, global review	Environmental, Economic, Social	Five-factor PI proposal
Ibáñez-Forés et al. (2019)	Spain	Social, Governance	Focus on social working conditions, safety, informal sector
Sasahara et al. (2024)	Brazil, Global South	Governance	Created MSW Governance Index

2.5.1 Technical Performance Indicators

Technical KPIs evaluate the physical and operational aspects of waste management, such as service coverage, collection and transport efficiency, infrastructure, and waste processing. They are among the most frequently evaluated in MSWM indicator frameworks, representing around 49.3% of total indicators, according to Cervantes et al. (2018). Collection coverage (% of the population serviced by waste collection) for example, is cited in 80% of indicator sets reviewed by Cervantes et al. (2018). This indicator is indeed fundamental, since a high coverage rate (ideally 100%) means that all the population has access to collection services and, supposedly, all generated waste is collected and brought into the system, preventing public health risks from uncollected waste. Similarly, waste generation (often measured per capita) is a key input indicator present in a majority of studies (Cervantes et al., 2018). It provides a baseline for quantifying the system and evaluating the success of waste reduction efforts (lower generation per person suggests more sustainable consumption) (AlHumid et al., 2019). Operational efficiency indicators are also prominent. Nearly half of the surveyed indicator sets studied by Cervantes et al. (2018) include measures of collection efficiency, such as route optimization or collection frequency, and the adequacy of collection containers. Around 20% of all the indicators were collection indicators, while 16.4% concerned treatment and recovery, nearly 14% disposal, 3.3% for street cleaning, and only 1.3% for prevention. Singh et al. (2025) identify a set of 20 technical indicators in four operational sectors: (a) street cleaning and maintenance, (b) waste collection and transportation, (c) recovery/recycling of materials, and (d) waste disposal practices. For street cleaning, they use KPIs like street-sweeping frequency and coverage, finding, for instance, that high-litter city centers received twice-daily cleaning while peripheral areas were serviced less frequently. For maintenance, the availability, condition and use of the equipment is mainly used, similarly to AlHumid et al. (2019). In the collection/transport category, technical KPIs include fleet adequacy, route efficiency, and collection rate. AlHumid et al. (2019) add indicators like waste separation rate at the source or the average distance between houses and (separated) bins. The recovery/recycling category of Singh et al. (2025) includes mostly indicators about waste separation at transfer stations and informal waste pickers, since they are the most important actors for recycling in developing countries. On the other hand, AlHumid et al. (2019) include the amount of recyclables, recycling rates and the presence of a material recovery facility (MRF) to evaluate the potential for recycling. Finally, for disposal practices, Singh et al. (2025) propose KPIs like the type of landfill, the number of informal waste pickers active at the site, and the percentage (or volume/weight) of waste disposed at the site, which is a common indicator present in more than one third of KPI sets (Cervantes et al., 2018). The proportion of waste disposed of at controlled facilities out of the total waste generated is also an official Sustainable Development Goal (SDG) indicator (SDG indicator 11.6.1) defined by the United Nations (UN-Habitat, 2025). AlHumid et al. (2019) additionally focus on indicators like leachate and waste composition of the landfill. However, these can be considered as environmental indicators, presented in the next section. AlHumid et al. (2019) interestingly add indicators concerning the staff productivity, such as the number of employees per ton of waste or per 1000 household, or the number of workers at landfills. These PI ensure staffing levels are balanced and can help drive resource optimization in order to find the equilibrium between operational quality and financial viability.

A benefit of technical KPIs is that they are often quantifiable and directly tied to service performance (e.g. tons collected per truck, or collection points served). They thus help identify operational bottlenecks. For instance, monitoring street-sweeping frequency and litter levels can help pinpoint where disposal practices needed upgrading (Singh et al., 2025). However, a key challenge with technical indicators is obtaining reliable data, especially in developing cities. Singh et al. (2025) note that lack of comprehensive and high-quality data often hinders informed decision-making in developing countries' MSWM systems. Even basic data like waste generation or collection coverage may sometimes be erratic.

2.5.2 Environmental Performance Indicators

Environmental KPIs assess the ecological outcomes of MSWM, including waste reduction, resource recovery, and pollution control. Interestingly, Cervantes et al. (2018) found that environmental metrics were included less often than technical ones, with fewer than 63% of the indicator sets they reviewed which had explicit environmental indicators. This underrepresentation in past frameworks is a concern, since waste management has significant environmental impacts, as explained earlier. Common indicators in this category are environmental quality measures, like leachate levels or emissions indicators. Although they have already been treated as technical indicators, indicators of waste recovery or treatment can also be considered as environmental KPIs, as they reflect how much waste is kept out of dumpsites (Sanjeevi and Shahabudeen, 2015).
Other environmental KPIs focus on pollution control at disposal sites. AlHumid et al. (2019) propose an "Environmental Endurance" category with detailed indicators for landfill impacts. For instance, they measure the visual and odor impacts of a landfill (qualitatively) to capture aesthetic nuisances that affect nearby communities. More technically, they evaluate leachate quality through parameters like Total Dissolved Solids (TDS), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), etc.. These indicators (EN3 through EN11 in AlHumid et al.) assess whether the landfill's environmental controls are effectively protecting soil and water. Tracking such indicators is beneficial because it provides early warning of pollution problems and can inform the need for better liners or leachate treatment systems (AlHumid et al., 2019). The obvious challenge, however, is that these advanced environmental KPIs require laboratory data and technical expertise that many municipalities (especially smaller or resource-constrained ones) may lack.

2.5.3 Economic and Financial Performance Indicators

Economic KPIs evaluate the cost efficiency and financial sustainability of MSWM services. Waste management often represents a significant portion of municipal budgets, around 20 to 40% of their total budget (Hanrahan et al., 2006). Therefore, tracking economic performance related to costs, revenues, and productivity is crucial for decision-makers. Cervantes et al. (2018) report that an "expenses" category was among the top three indicator categories in prior studies. Common examples include cost per ton of waste handled, annual MSWM expenditure per capita, and revenue recovery rates. One specific KPI frequently mentioned is the unit cost of waste disposal or collection proposed by AlHumid et al. (2019),and Sanjeevi and Shahabudeen (2015). Monitoring cost per ton helps in benchmarking efficiency, as a rising unit cost might indicate inefficiencies or escalating expenses (fuel, labor, etc.), whereas a relatively low cost per ton might indicate better optimization or economies of scale.
Singh et al. (2025) also introduce a Recyclable Market Value (RMV) index, which assigns economic value to recovered materials in order to measure how much monetary value can be extracted from the waste stream. In their case study, the relatively high RMV of street-collected recyclables suggests the opportunity that if those materials are retrieved and sold, the municipality or the informal sector can gain financially.
The benefit of economic KPIs is quite straightforward: they introduce accountability for how resources are used and ensure that MSWM systems are financially viable in the long run. These indicators are also important for gaining political and public support. For instance, demonstrating a reduction in cost per ton after a new program can justify that program's continuation or expansion. The challenge, however, is that financial data must be transparent and consistently tracked. In some cities, especially where multiple agencies or private

contractors are involved, consolidating the full cost data (including hidden subsidies or externalities) can be difficult. Also, it is important that economic KPIs remain in balance with others KPIs in order for cost cutting strategies to not hinder performances.

2.5.4 Social Performance Indicators

Social KPIs cover the community and human aspects of MSWM, such as user satisfaction, public health, inclusion of stakeholders, like informal workers, and public participation in waste activities. These indicators acknowledge that MSWM is a public service and must meet the needs and expectations of the community. According to Cervantes et al. (2018), social attributes were among the most frequently addressed in existing indicator sets, on par with technical factors. A primary social indicator is the customer or citizen satisfaction with waste services, as porposed by AlHumid et al. (2019), Ibáñez-Forés et al. (2019), and Sanjeevi and Shahabudeen (2015), which can be measured through surveys or number of complaints. A high percentage of dissatisfied residents would flag problems like unreliable collection or dirty streets, pushing management to investigate and improve, while quick response to complaints is noted as an important action for improving public satisfaction. Service coverage, discussed earlier as a technical metric, can also be considered as a social indicator because of its impact on the population. 100% collection coverage means no community is left with unmanaged waste, thereby protecting all citizens' health. Social inclusion in MSWM is also measured by KPIs related to the level of public participation (AlHumid et al., 2019; Ibáñez-Forés et al., 2019; Sanjeevi & Shahabudeen, 2015). They can be defined qualitatively with indicators such as community involvement in improving practices, public acceptance of waste management plans, and public awareness about the importance of SWM. They are measured, for example, by surveying residents on whether they take part in recycling programs, awareness campaign, or support new waste policies. The challenge is that these indicators require sociological data collection (surveys, interviews) and clear criteria to score performance. However, including them ensures the MSWM system is evaluated not just on tons and dollars, but also on community well-being and participation.

In developing country contexts, informal sector involvement is also a major social factor as well. Singh et al. (2025) explicitly recommend using their performance assessment to support the informal sector's role through incentive schemes. A social KPI here could be the number of informal workers integrated or supported in the formal system through cooperatives or other, or the proportion of recyclables collected by the informal sector. These indicators recognize the social reality of who is doing the work of recycling on the ground and aim to improve their working conditions and efficiency. In this regard, Ibáñez-Forés et al. (2019) go further by assessing additional social conditions of workers such as fair salary (compared to the legal minimum), legal employment, and occupational health and safety, which are rarely addressed in traditional MSWM evaluations. They also propose indicators linked to workers' education levels, children's school attendance, and even housing conditions, emphasizing that social KPIs should reflect the broader life circumstances of waste sector workers.

2.5.5 Governance and Institutional Performance Indicators

Governance and institutional KPIs assess the policy, regulatory, and institutional conditions that enable or constrain MSWM. These indicators are less about what is done (tons collected, etc.) and more about how the system is managed and sustained. Sasahara et al. (2024) developed the Municipal Solid Waste Governance Index (MSWGI) to address this gap, applying it across over 5,000 Brazilian municipalities. The index is structured around three dimensions: regulatory quality, voice and accountability, and government effectiveness. The indicators of regulatory quality include, for example, the existence of a municipal waste management plan or the presence of legislation on single-use plastic (or others). Voice and accountability indicators consist of available/public data on MSWM, the existence of municipal control/environment councils, or the access to information for citizen and the possibility to complain or consult. Finally, the government effectiveness is measured through some of the technical and other indicators mentioned in previous sections. These KPIs reflect the formal presence of laws or plans, but also their implementation and the degree of public involvement.

2.5.6 Selection of KPIs for the Essaouira case study

A final set of KPIs shown in Table 2 was selected on the basis of the literature review in order to assess the performance of the MSWM system in Essaouira, taking into consideration the context and characteristics of the city, such as its coastal and touristic profile with both urban and rural zones.

Technical indicators were chosen to evaluate the basic functioning and efficiency of the MSWM system. Metrics such as collection coverage is a non-negotiable KPI for Essaouira. Ensuring that 100% of the city's waste is collected is essential in a city which depends so heavily on tourism. The collection frequency and the general condition of communal containers are important to understand the reach and reliability of collection services. Street cleaning frequency and coverage, as well as the presence of public bins are useful to evaluate the cleanliness of the public spaces. The waste generation per capita and workers per ton of waste cannot be forgotten either, as they provide insight into the scale of waste produced and the human resources allocated to manage it. Moreover, treatment-related indicators, such as separation at source, recycling rate, and presence of an MRF reflect the city's ability to divert waste from landfilling and adopt sustainable practices. Finally, landfill-related indicators (condition and share of waste disposed) provide insight into the final disposal stage, which is often the weakest point in developing contexts. Indicators for labour productivity could also have been included in the KPI set, however, such information was complicated to obtain during the field visit and they were thus removed.

Environmental indicators were selected to assess the impact of waste management practices on the surrounding ecosystem and public health. The presence of open or wild dumps is a critical indicator in developing contexts, as these sites often lead to uncontrolled pollution and pose risks to nearby communities, animals, and natural areas. Leachate quality (e.g., BOD, COD, TDS) is a key parameter for evaluating groundwater and soil contamination risks from landfill sites.

For the **economic indicators**, the cost per ton of waste handled and the annual MSWM expenditure per capita should be used to measure the investments of the municipalities relative to their waste and population. However, during the fieldwork, only the total budget per year was for MSWM was collected, and it could not be separated into collection, treatment, cleaning, awareness, etc. Therefore, the cost per ton of waste handled could not be computed and was removed from the list. Also, the Recyclable Market Value (RMV) assesses the economic potential of materials that could be recovered, an increasingly important metric for promoting circular economy strategies and reducing dependence on landfilling.

In the **social indicators**, the citizen satisfaction concerning waste collection and public property reflects public perception of service quality can reveal gaps in performance that technical indicators may overlook. The public participation in MSWM programs also helps to gain insight on the public behaviour, especially in a context where behaviour change is needed to support waste reduction and sorting at source. Informal sector presence and integration were also included, as informal waste collectors play a significant role in resource recovery in many Moroccan cities.

Finally, **governance indicators** like the existence of a municipal waste plan were chosen, as it is a fundamental indicator of strategic planning and alignment with national policies. The presence of legislations (on single-use plastics or littering) and their enforcement reflects the municipality's commitment to waste prevention and environmental protection, particularly relevant in touristic and coastal cities facing plastic pollution. The existence of a municipal environmental council or control council shows the level of transparency and control of the municipality over the different MSWM activities.

To facilitate a more coherent and quantifiable analysis, the individual indicators listed in Table 2 were grouped into a smaller set of consolidated KPIs. This approach was adopted because of the fact that many of the original indicators are closely related or measure overlapping dimensions of the MSWM system. Each consolidated KPI thus represents a critical dimension of performance while allowing for clearer comparisons and interpretation in later chapters. The consolidated set can be found in Table 3.

Table 2: Key Performance Indicators for MSWM Evaluation in Essaouira

Indicator	Explanation	Unit
Collection coverage (%)	Proportion of population or area receiving regular waste collection services	%
Collection frequency	Number of times waste is collected per week	collections/week
General condition of waste containers	Percentage of bins/containers observed to be overflowing or in bad condition	%
Cleaning frequency	Number of times public spaces are cleaned per week	cleanings/week
Cleaning coverage	Proportion of public spaces covered by cleaning services	%
Presence of public bins	Presence of public bins in highly frequented areas	Qualitative
Waste generation per capita	Average amount of waste generated per person per day	kg/capita/day
Waste separation at source	Existence and extent of household-level waste sorting	Yes/No or % households
Recycling rate	Share of total waste that is recycled	%
Presence of MRF	Availability of a facility for sorting and recovering recyclables	Yes/No
Landfill condition	Overall operational and environmental state of the landfill, scored via a checklist.	Qualitative
Waste disposed at landfill (%)	Proportion of total waste sent to landfill	%
Presence of open dumps	Existence of illegal or uncontrolled dumping sites	Yes/No
Leachate quality	Indicators of leachate pollution at disposal sites (COD and BOD/COD ratio)	Categorical
Annual MSWM expenditure per capita	Total yearly spending on MSWM per resident	MAD/capita/year
Recyclable Market Value (RMV)	Potential revenue from selling recyclable materials	MAD/year
Citizen satisfaction in collection services	Level of public satisfaction with waste collection services	Survey score
Citizen satisfaction in public property	Level of public satisfaction with public property	Survey score
Public participation	Extent of community involvement in MSWM programs	Qualitative
Informal waste pickers presence	Degree to which informal waste pickers are active in the MSWM system	Qualitative
Informal sector integration	Degree to which informal waste workers are recognized or supported	Qualitative
Existence of municipal waste plan	Presence of an official local strategy for waste management	Yes/No
Plastic and Litter Regulation	Degree to which legal measures on plastic use and littering exist and are enforced at the local level	Qualitative
Environmental Oversight and Citizen Access	Existence of a municipal body that monitors MSWM performance and provides a channel for citizen complaints or feedback	Qualitative

Table 3: Consolidated KPI set for MSWM Performance Evaluation

Consolidated KPI	Definition / Included Indicators
Collection Efficiency	Collection coverage, Collection frequency, Waste separation, General condition of waste containers, Citizen satisfaction with public property
Public Space Cleanliness	Cleaning frequency and coverage, Presence of public bins, Citizen satisfaction with collection services
Waste Generation Rate	Waste generated per capita per day
Waste Recovery	Waste separation at source, Recycling rate, Presence of MRF
Waste disposal	Landfill condition, % of waste landfilled, Presence of open dumps, Leachate quality (BOD/COD/TDS)
Financial Sustainability	MSWM expenditure per capita, Recyclable Market Value (RMV)
Public Engagement	Public Participation
Informal Sector Role	Informal waste pickers presence, Informal sector integration
Institutional Framework	Existence of municipal waste plan, Plastic and litter regulation, Environmental Oversight and Citizen Access

2.6 Best Practices in MSWM – Developed Countries Context

This section examines best practices in MSWM from developed countries, with a primary focus on European Union Member States. These cases offer valuable insights into effective legal frameworks, collection systems, treatment technologies, and public engagement strategies. By identifying the key instruments and governance models that drive high-performance waste systems in these countries, this review lays the groundwork for designing context-appropriate recommendations for Essaouira and other developing regions.

2.6.1 Policy and Governance Approach

European countries share a common policy framework guided by the EU waste hierarchy and EU directives. These instruments create a foundation for all Member States (MS), ensuring shared goals in environmental protection, circular economy principles, and long-term performance targets.
The cornerstone of EU waste legislation is the **Waste Framework Directive (2008/98/EC)**. It defines key terms (e.g., waste, recovery, disposal), introduces the waste hierarchy (prevention, reuse, recycling, recovery, disposal), and sets binding targets for MS. It also mandates separate collection and promotes EPR schemes. The WFD requires each MS to adopt waste prevention programs and national waste management plans.
Supporting this is the Landfill Directive (1999/31/EC), which restricts landfilling by requiring pre-treatment of waste, setting reduction targets for biodegradable municipal waste, and mandating long-term monitoring of gas and leachate emissions for at least 30 years after closure. The Industrial Emissions Directive (2010/75/EU) governs incineration facilities, imposing strict pollutant limits and requiring use of Best Available Techniques (BAT), making waste-to-energy an environmentally safer option for non-recyclables. Specific waste streams are addressed by the Packaging and Packaging Waste Directive (94/62/EC, amended by 2018/852), which sets recycling targets for materials like plastic, glass, and paper, and mandates EPR for packaging producers. Finally, the Single-Use Plastics Directive (2019/904) bans the most polluting plastic items, introduces consumption reduction targets, and promotes deposit-refund systems to boost collection and recycling rates.

This set of regulations and directives have set ambitious targets for all of the 27 MS concerning municipal waste management. These targets, set for 2025 notably include the recycling of minimum 55% of all municipal waste, and 65% of packaging waste (with specialized rates for each material). A 10% cap on landfilling is also set for 2035 (European Environment Agency, 2023a).
In order to respect these targets, different MS have begun implementing waste prevention plans. A regional trend is observed, as northern European countries tend to be more effective in implementing these measures. Indeed, countries such as Sweden (SE), Germany (DE), Belgium (BE), Denmark (DK), or the Netherlands (NL), analyzed for this study, show promising results in terms of recycling and landfilling rates, and several legal instruments or governance strategies are the root of these successes.

Landfill bans and taxes are among the most impactful tools. Malek et al. (2023) found that banning landfilling of untreated waste is statistically associated with sharp decreases in landfill use and corresponding increases in recycling and waste-to-energy treatment. Early warning assessment reports from the EEA (2022) show that the five countries mentioned above introduced a landfill ban on several types of waste, notably recyclable and biodegradable ones. Except for Germany, where the landfill ban is sufficient to strongly decrease landfill rates, all these countries have also implemented a landfill tax, which can range from 30 to 110 EUR per ton of waste disposed of. These levies make disposal financially unattractive, incentivizing recycling and incineration with energy recovery. Many countries (BE, NL, DK, SE) pair these with **incineration taxes or caps** to avoid simply shifting all waste to combustion, aiming to push materials further up the ladder to recycling.

Other disincentives to encourage waste reduction is the introduction of **"Pay-As-You-Throw" (PAYT)** systems, which have also been adopted by the five countries. The goal of this system is to apply the polluter-pays principle to household waste. Under PAYT, residents pay user fees based on the amount of residual (non-recycled) waste they dispose of (by weight, volume or per bag). Card and Schweitzer (2022) investigated PAYT schemes in the BENELUX and found that these have led to significant reductions in residual waste generation, with up to 25% less waste per person compared to non-PAYT schemes.
Out of the five countries analyzed here, Belgium and the Netherlands are the most advanced countries for this scheme, with widespread use for BE (especially in Flanders), and 50% of its municipalities (mostly rural), or 37% of the population covered for NL. The remaining countries implemented PAYT more locally in some municipalities (European Environment Agency, 2022).

Incentive programs also exist, such as **Deposit-refund systems (DRS)** for beverage containers. They are a form of EPR that directly engages consumers by adding a small deposit to bottles/cans that is refunded upon return. These schemes achieve very high return rates, up to 90% (Platform, 2022). Malek et al. (2023) found that deposit-refund policies correlate with lower overall landfill volumes. No correlation with reduction in total waste generation was found, but it is believed that consumers become more conscious of waste with this system.

Except for Belgium which only has some pilot projects, DRS schemes (mainly for plastic bottles and cans) are present in all the five countries mentioned above (European Environment Agency, 2022).

Finally, as introduced in Section 2.1, **EPR schemes** are another cornerstone of the frameworks implemented. In these programs, producers of packaging, electronics, batteries, and other products are legally obliged to fund or manage the collection and recycling of their goods at end of life. They also relieve municipalities of some financial burden and have driven higher recycling rates for those materials across Europe. All five countries introduced EPR systems for packaging. While, Germany and Belgium have long-standing, advanced systems, the Netherlands and Sweden are improving theirs, and Denmark has passed EPR legislation but will only fully implement it by 2025 (European Environment Agency, 2022).

Overall, the governance of MSW in Europe is typically multi-level, combining national oversight with strong roles for local authorities. National governments usually set frameworks (e.g. laws which transpose EU directives, binding targets, landfill quotas) and often use economic instruments (taxes, subsidies) to guide behavior. But the execution of waste services happens at the municipal or regional level. High-performing countries often have a well coordinated governance. For example, Germany has a federal system where municipalities manage waste collection, but a centralized body (the Zentrale Stelle) oversees producer responsibility, ensuring strong national coordination (European Environment Agency, 2022, DE report). In Belgium, responsibilities are split across regions (Flanders, Wallonia, and Brussels), with Flanders achieving higher performance due to stricter enforcement and more comprehensive monitoring (European Environment Agency, 2022, BE report). By contrast, Sweden and Denmark delegate much of the implementation to municipalities, but suffer from limited enforcement mechanisms and inconsistent local application, especially in bio-waste collection (European Environment Agency, 2022, SE and DK report). The Netherlands, while decentralized, maintains effective oversight through strong data systems and national targets, although enforcement relies more on cooperation than on sanctions (European Environment Agency, 2022, NL report).
Moreover, transparency and data reporting are key governance strategies as well. Most EU countries monitor municipal recycling rates and publish their performances, which creates accountability and knowledge-sharing between cities and countries.

2.6.2 Collection and Logistics Systems

European MSW collection systems have evolved to maximize **source separation** efficiency while integrating modern logistics for cost-effectiveness. A high degree of source-separated collection is now standard across developed European countries, as separating waste at the source yields cleaner recyclable streams and higher overall recycling rates. Most municipalities provide separate bins or containers for key fractions, typically at least: organics (food and green waste), paper/cardboard, glass, plastics & metal (often combined or further separated), and residual waste. Many regions also collect hazardous household waste and e-waste separately at drop-off points or periodic curbside collections. This multi-stream approach is backed by EU requirements, which mandated the separate collection of paper, metal, plastic, glass, and bio-waste.
However, implementation varies by country (European Environment Agency, 2022). Germany and Belgium (especially Flanders) have long-established, well-structured systems with high coverage of door-to-door collection for recyclables and organics. Germany typically has 90% separate collection coverage. In Sweden and Denmark, the rollout of bio-waste separation has been slower and more fragmented, especially in multi-family housing, where participation is lower and logistical challenges persist. The Netherlands offers municipalities flexibility, reaching a collection rate of 59% of plastic was source-separated in 2020. Some municipalities collect plastic packaging separately at the source, while others rely on post-sorting from mixed waste, a practice also observed in parts of Denmark and Brussels, though it often leads to lower material quality and capture rates.
Urban–rural disparities are common in all countries, with rural areas typically showing higher separation performance due to easier logistics and stronger community compliance.

Beyond the separation of waste streams, **logistics optimization and digitalization** have become important points for improving collection efficiency. Municipal waste collection is a resource-intensive operation traditionally based on fixed routes and schedules, which results in unnecessary trips for example to empty half-empty containers (CORDIS, 2019). To address these inefficiencies, cities across Europe are adopting "smart" waste collection systems. One major innovation is the use of Internet of Things (IoT) sensors in waste containers to monitor fill levels in real time. In 2023 the city of Madrid began installing over 11,000 smart sensors on street containers, paired with a cloud-based platform for route optimization (Candam, 2023). These sensors report how full each bin is, allowing collection trucks to be dispatched only when and where needed. The data-driven route planning can create dynamic collection schedules that respond to actual waste levels, factoring in truck capacity, traffic conditions, and collection deadlines, allowing to service up to 40% additional containers with the same fleet resources.
Technology is also used for PAYT systems, as RFID tags are present to track individual bins in order to follow,

measure and bill each household's waste stream.

Another aspect of modern MSW logistics in Europe is integration and regional optimization. Rather than each city working in isolation, there is often coordination among municipalities to share facilities and optimize transport distances. For example, transfer stations are used to consolidate waste from local collection trucks and then haul it in bulk to distant treatment plants (incinerators, recyclers) more economically. On the operational side, contracting with private waste firms under competitive tenders is common in Europe, often with requirements for route optimization and fleet modernization written into contracts by city authorities.

2.6.3 Waste Treatment and Recovery Technologies

MSW that has been collected in Europe is directed into a range of treatment and recovery pathways, with an emphasis on technologies that recover value and minimize environmental impact. The most common treatment for residual (non-recyclable) waste in advanced European countries is the incineration with energy recovery or biological treatment for organic waste.

Waste-to-Energy (WtE) incineration consist of burning the waste in specialized facilities in order to capture the energy released and transform it into heat and electricity. This technology is widespread in countries such as Sweden, Denmark, the Netherlands, Germany, and Belgium (European Environment Agency, 2022). Modern European WtE plants are far away from the polluting incinerators of the past. Indeed, decades of tightening EU emissions standards have driven the adoption of effective air pollution control, so that pollutants like dioxins, NOx, and particulate matter are largely eliminated from flue gases. According to Brunner and Morf (2024), today's WtE is "one of the best investigated and optimized technologies in waste management" capable of simultaneously reducing the volume of waste, destroying organic pollutants, and recovering useful energy. They also note that WtE plays an essential role in a circular economy by "cleaning" material cycles. This means that WtE can safely handle the fraction of waste that cannot be recycled (often contaminated or composite materials), converting it to stable residues and energy. Many facilities now also recover materials from the ashes. For example, ferrous and non-ferrous metals are extracted from bottom ash in most plants, and the rest of the ashes can be safely reused in construction after treatment (Brunner and Morf, 2024). Other non-reusable ashes must be treated or disposed of safely.
Overall, these technologies can convert waste into electricity with around 20–30% efficiency, while heat efficiencies may by around 60–85%. In total, conversion efficiencies are approaching 100% (Fruergaard et al., 2010).

Beyond incineration, several countries invest in **biological treatment**, notably composting and anaerobic digestion for organic waste streams. Biological treatments are crucial, as around 30 to 40% of total MSW in the EU is organic biowaste (Interreg Europe Policy Learning Platform, 2021). Flanders (Belgium) and Germany are frontrunners in this area, owing to their mature bio-waste collection systems. However, in Sweden, Denmark, and Brussels, the uptake of these technologies is limited by low bio-waste capture rates, especially in apartment buildings, where separation compliance remains a challenge. This results in underutilized composting and digestion capacity (European Environment Agency, 2022).
Several southern European countries face a similar challenge, because of their lack of source separation. But, to address these shortcomings, some municipalities have implemented home and community composting initiatives to manage organic waste directly at the source. For example, the Greater Porto area (Portugal) distributed free composters and provided training to residents, resulting in significant waste diversion, up to 423 kg annually per traditional composter. Similarly, in Casalgrande (Italy), financial incentives such as a 20% waste fee reduction encouraged citizens to compost at home, reducing the volume of putrescible waste entering municipal systems (Interreg Europe Policy Learning Platform, 2021).
In parallel, anaerobic digestion is gaining traction across Europe as a means to manage biowaste and to produce renewable energy. When digestate from this process is used as compost or fertilizer, the treatment qualifies as recycling under EU law. Countries like Bulgaria, Italy, and Greece have demonstrated successful models where biogas plants process kitchen and agricultural waste to produce energy and soil amendments, often in cooperation with local authorities or farming cooperatives (Interreg Europe Policy Learning Platform, 2021).

The lack of source separation in many European countries can lead to the introduction of **Mechanical-Biological Treatment (MBT)**. MBT is a hybrid technology that combines mechanical sorting with biological processing to treat mixed municipal waste. In a typical MBT plant, incoming residual MSW is first mechanically processed. Recyclables (metals, some plastics/paper) are extracted, and the high-calorific fraction (shredded plastics, paper, wood) are separated as RDF (Refuse-Derived Fuel) for use in cement kilns or dedicated RDF incinerators. The remaining largely organic-rich fraction then undergoes a biological treatment step (either aerobic composting or anaerobic digestion) to be stabilized. The outputs can either be used as compost/fertilizer, or are disposed of, because of the contamination of the initial waste (Amato et al., 2022).

Generally, these facilities are not very present in most developed countries (BE, DK, DE, SE, NL) due to their high-quality source separation. However, in countries such as Italy, Spain, Greece, or Poland, MBT are widely used for RDF production and organic waste stabilization (European Environment Agency, 2022 IT, ES, GR, PL reports). When organic waste is stabilized via MBT, the total volume is reduced and the waste will generate far less methane and leachate when landfilled afterwards. However, the performance of MBTs can vary, and some studies report modest material recovery rates and question the quality of the stabilized output (Amato et al., 2022). Therefore, MBT is considered a viable bridge technology before reaching proper source separation.

Overall, the **recycling rates** vary significantly across countries from the EU. Germany leads in terms of MSW recycling with a rate of 67%, or 62% when adjusted to the stricter EU methodology, while Belgium leads for recycling of packaging. Out of the 27 MS, only 9 are not a risk of not meeting both recycling targets, 8 are at risk of missing one of the two, and 10 are at risk of not meeting both (see Figure 6). As for special material recycling, 19 countries are struggling to meet the 50% recycling target for plastic packaging.
High-performing countries typically combine landfill bans or taxes, accessible bio-waste collection, and economic incentives like PAYT to drive better recycling outcomes.

The average **prices of secondary materials** in 2023 were around 95€/ton for glass, 156€/ton for paper and cardboard, and 321€/ton for plastic (Eurostat, 2023).

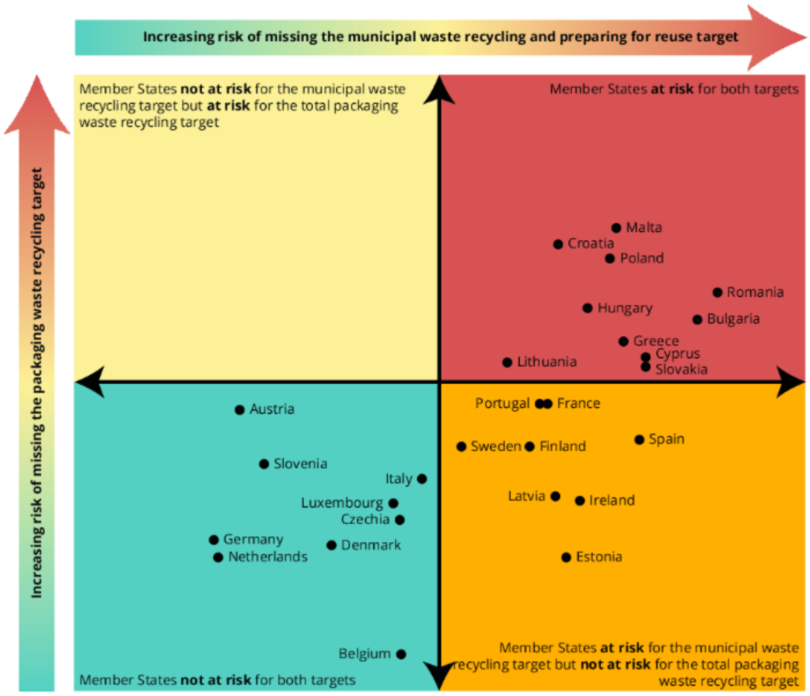


Figure 6: "EU Member States' prospects of meeting the recycling targets for municipal waste and packaging waste" (European Environment Agency, 2023a)

2.6.4 Waste Disposal

Finally, when the waste cannot be recovered via any of the previously mentioned technologies, it is disposed of in a **landfill**. It must however be pre-treated before being landfilled, and it is checked to ensure its adheres to several criteria (European Union, 1999). In the most developed countries of Europe, such as Germany, Belgium, the Netherlands and Sweden, landfilling rates are below 2-1% (European Environment Agency, 2022). In these nations, landfilling is used as a very last resort to take care of waste, and it is generally limited to inert residues (e.g. incinerator ash after metal recovery). In less developed countries (Southern and Easter Europe) biodegradable waste fraction are also landfilled, as explained previously. Therefore, in Italy, Spain, Poland, and Greece, landfilling rates range from 20 to 50% (European Environment Agency, 2022), which is still far above the limit set for 2035.
However, when landfills are used, European best practices focus on sanitary landfill design and aftercare to mitigate environmental impact. This includes engineered liners and leachate collection systems to protect soil and groundwater, as well as landfill gas extraction systems. It is required by EU Landfill Directive that landfills capture methane gas generated from waste decomposition. The gas collected is either flared or used for energy (generating electricity or heat). Many older landfills have been retrofitted with gas wells, and EU regulations

require continued gas and leachate management for decades after a landfill's closure. This is called the aftercare period. The EU Landfill Directive also requires the operator of a landfill to ensure the aftercare for "as long as the landfill poses a hazard with a minimum period of at least 30 years" (European Union, 1999). However, this specific regulation can cause financial problems for the landfill operator, as no money is generated during that period because no waste entries occur. Therefore, the Netherland adopted measures to counter that problem. After closure and capping of the landfill, the aftercare responsibilities are transferred to the province, so that aftercare problems can be handled with available financial support (Interreg Europe, 2019).

In recent years, a cutting-edge approach to landfilling was developed. It is the concept of "aerobic" or bioreactor landfills, which aim to actively accelerate waste stabilization. In a conventional landfill, anaerobic decomposition can take many decades to break down organic matter. By contrast, injecting air (or liquids) into the waste mass can promote faster aerobic degradation. Studies have shown that such aerobic bioreactor landfills (ABL) could shorten the stabilization period of waste by decades (Ritzkowski and Stegmann, 2012). The faster stabilization means a quicker decline in gas and leachate emissions and could allow the landfill to be repurposed or closed sooner, with less aftercare work. A notable example is the Braambergen landfill pilot in the Netherlands, which I previously studied in a 2024 course assignment on sustainable landfill management. Starting in 2017, several compartments of the Braambergen site have been subjected to in-situ aeration treatment. Operators installed around 230 injection/extraction wells across 10 hectares of the waste mound to circulate air through the waste and actively extract landfill gas. Early findings indicate accelerated decomposition and reductions in leachate pollution indicators, validating the approach's potential.
Furthermore, some countries are even exploring "landfill mining", which essentially consists of excavating and recovering materials from old landfills once the waste has been rendered inert (Toto, 2020). While not yet widespread, these forward-looking projects underscore a broader principle in Europe: the end goal is to phase out landfilling.

2.6.5 Public Engagement and Behavior Change

Technical solutions and policies in MSW management are only as effective as the public's participation in them. Thus, European countries have devoted significant effort to engaging citizens in waste reduction, source separation, and proper disposal behaviors. A combination of economic incentives, public education, convenient services, and social initiatives is used to encourage behavior change and sustain high participation rates in recycling programs.

One key strategy is the use of **economic instruments** that directly incentivize households to produce less waste and to sort recyclables. The PAYT schemes discussed earlier are not only policy tools but also behavior-change tools. When residents see a direct fee tied to how much trash they throw out, they are motivated to recycle more and avoid waste. Experience in multiple EU countries shows PAYT can change habits and result in lower (residual) waste generated (Card and Schweitzer, 2022).
Similarly, deposit-return systems on bottles and cans motivate consumers (including children) to return empties. The financial reward, although small, taps into an intuitive behavior, as people tend not to throw away something with a monetary value. Many countries also enforce fines or penalties for improper waste disposal (for instance, illegal dumping or putting recyclables in the trash in violation of local rules), although enforcement intensity varies. Card and Schweitzer (2022) highlight the importance for these instruments to be accompanied by efforts to maintain public acceptance, such as funneling back revenues from waste fees or taxes into improved services, and for governments to emphasize fairness. For example, offering discounts or accommodations for low-income households, and ensuring that everyone has access to recycling facilities so that incentives are seen as equitable.

Another pillar of public engagement is **education and information campaigns**. European municipalities and environmental agencies invest in continuous outreach to inform residents *why* and *how* to participate in waste programs. Indeed, waste prevention reports from Belgium, Germany, the Netherlands, Sweden, and Denmark, show that a wide range of initiatives have been developed to educate citizens, encourage behavioral change, and foster a culture of sustainability rooted in everyday practices (European Environment Agency, 2023b).

Overall , national campaigns play a crucial role in raising awareness and shaping consumption habits. In Germany, for example, the campaign "Zu gut für die Tonne" targets food waste reduction by informing households, hospitality businesses, and retailers (European Environment Agency, 2023b, DE report). Similar efforts can be observed in the Netherlands, where initiatives such as "#Verspillingsvrij" and "Iedereen doet wat" combine media outreach with practical advice to engage the public in circular practices (European Environment Agency, 2023b, NL report). In Sweden, the government runs the "Hallo Konsument!" platform, offering independent information to support sustainable consumption choices, while Denmark reaches younger audiences through its "Mind the Trash" educational modules aimed at schoolchildren (European Environment Agency, 2023b, SE and DK reports). Belgium, with its regionally organized strategies, runs targeted campaigns in Brussels, Flanders, and Wallonia that promote zero-waste lifestyles, reuse, and sorting practices (European Environment Agency, 2023b, BE report).

Education is another pillar of engagement. Waste prevention is increasingly integrated into school curricula across these countries. The Netherlands has developed programs such as “Waste at School,” which combines behavioral insights with learning materials for teachers and municipalities. In Belgium and Sweden, environmental education is embedded in both primary and secondary education, and Denmark supports the creation of school-specific resources that foster critical thinking around consumption and resource use (European Environment Agency, 2023b). The European Commission also organizes courses and seminars to form teachers and educators to sustainability and waste management education ((European Commission, 2025a)), as well as recycling incentive programs for schools in some countries (e.g. European External Action Service, 2025). By addressing students early, these countries aim to install long-term habits for waste prevention and circular economy principles.

In addition to formal education, community-based initiatives are used to encourage reuse and repair. Germany, Sweden, and the Netherlands have built extensive networks of Repair Cafés, while Denmark’s Aarhus REUSE Center and Sweden’s Fixotek centers offer physical spaces for citizens to borrow tools, repair items, and donate or exchange goods. These facilities not only reduce waste but also create spaces for social interaction and collective learning. Public authorities often support such initiatives through tax incentives, subsidies, or communication campaigns that promote local circular hubs and second-hand culture (European Environment Agency, 2023b).

Finally, local and regional governments play a key role in tailoring engagement strategies to specific contexts. The city of Kiel in Germany developed its Zero Waste City strategy through a participatory process involving residents, while Dutch cities like Groningen host circular economy incubators that unite schools, startups, and civil society around sustainability goals. In Denmark and Sweden, municipalities are encouraged to develop their own reuse and anti-littering plans, often with support from national agencies. Overall, a lot of support is offered by municipalities and authorities for sustainable initiatives.

In sum, developed European countries are adopting a multifaceted and inclusive approach to public awareness and engagement in MSW prevention. Rather than treating citizens as passive recipients of policy, these strategies empower individuals and communities to take active roles in building more sustainable waste systems. By combining education, communication, incentives, and local participation, these countries foster not only improved waste outcomes but also a deeper cultural shift toward circular and responsible living.

3 Methodology

This chapter outlines the methodological approach adopted to conduct this thesis, which is structured in two main phases: a diagnostic phase and a strategic phase. The diagnostic phase focuses on assessing the current state of MSWM in Essaouira, based on the previous literature review and on results from the fieldwork conducted in 2025. The fieldwork includes stakeholder interviews, on-site observations, and a local survey. This phase aims to identify key inefficiencies and performance gaps in the system through both qualitative insights and a structured evaluation using selected KPIs. The strategic phase then builds on these findings to formulate targeted recommendations. It draws on a review of international best practices and relevant policy frameworks, prior knowledge, and additional literature.
This dual approach was selected to ensure that recommendations are both locally grounded and aligned with globally proven strategies. The sections below detail the fieldwork methods, data collection tools, KPI evaluation framework, and the approach used to build strategy-oriented recommendations tailored to Essaouira's local context.

3.1 Data Collection for the Diagnostic Phase

The data collection for the Diagnostic Phase combined a preliminary literature review (see Chapter 2) with qualitative fieldwork conducted in Essaouira in April 2025. The literature review focused on the general principles of MSWM, the current state of MSWM in Morocco and specifically in Essaouira, and the legal and institutional frameworks guiding waste management. Sources included academic articles, government reports, and international development documents. The review helped identify key challenges, actors, and gaps in data availability, and provided a foundation for the subsequent field research.

The fieldwork was carried out over 17 days and involved a combination of stakeholder interviews, on-site observations, informal interactions, and a local resident survey. The objective was to gather first-hand insights on waste generation, collection and cleaning practices, public engagement, landfill operations, and recycling pathways. Overall, the majority of primary data was obtained through discussions, which offered access to information not available in official documents or online reports, thereby enriching the analysis with firsthand accounts and site-specific knowledge.

3.1.1 Stakeholder Interviews

A series of semi-structured interviews were carried out with a diverse range of stakeholders. For each meeting, a questionnaire was prepared to guide the discussion (see Appendix A.1 to A.5). However, interviews were conducted in a flexible and conversational format. This approach allowed for spontaneous follow-up questions and the collection of more nuanced responses. Interviews were not recorded, and instead, handwritten notes were taken during each session.

The fieldwork began with meetings at the **Superior School of Technology in Essaouira (ESTE)**, including discussions with the director and a professor from the environmental department. However, no MSWM-specific research had been conducted by the institution, and no local data on waste volumes or characterization was available. Nevertheless, first information on common practices and active stakeholders in the municipality were shared.

Further interviews included the **director of Essaouira's beach management**, who had previously been involved in initiatives such as the TouMaLi project (see Section 2.3.3 and 4.4.3). He provided insight into the broader waste management landscape in Essaouira, shared preliminary information on collection services (ARMA, see Section 4.2), and elaborated on upcoming municipal initiatives (see Section 4.4.3)

Then, discussions were held with **municipal staff**, particularly the **head of the Technical Division**. He granted access to internal data related to landfill operations (see Section 4.4.1), upcoming waste treatment projects (see Section 4.4.3), and the ARMA contractual framework (see Section 4.2). He also facilitated a site visit to the Essaouira landfill, which is typically restricted to external visitors.

Key actors from the informal and private recycling sectors were also consulted, including the founders of **MIKA** and **TRIVALDEC**, two organizations engaged in the recovery and resale of recyclables. These discussions shed light on alternative recycling pathways and the integration (or lack of it) of informal actors in the MSWM system (see Section 4.4.2).

The **president of Surfrider Foundation's local antenna in Sidi Kaouki** was interviewed to get a better understanding of the awareness programs in place, and one of their awareness-raising campaigns was attended in order to observe on-the-ground educational efforts (see Section 4.5).

Despite attempts, a meeting with ARMA's supervisory staff could not be arranged due to an ongoing transition in leadership. Nevertheless, extensive information on ARMA's operations was gathered through the municipality, which directly oversees and mandates the contractor's activities.

Due to busy schedule and school holidays occurring at the time of the fieldwork, no interview with schools could be organized. However, local contact at the ESTE agreed to conduct the small interview after my departure. A questionnaire was sent and a few responses came back in time for the analysis of the Diagnostic Phase (see Section 4.5).

3.1.2 Resident Survey and Local Interactions

To capture public perception, a survey was distributed among local residents, both in person and online via Google Forms (see Appendix A.6). The questionnaire was translated into Arabic using the local dialect to ensure accessibility for everyone. The survey addressed topics such as participant's habits and practices concerning MSWM, satisfaction with collection services and general cleanliness (see Sections 4.2 and 4.3), and awareness of waste-related issues (see Section 4.5). A total of 112 responses were collected.

Moreover, informal conversations were held with **ARMA'staff** to get insights on work conditions and challenges, although the language barrier complicated the exchanges (see Section 4.3). Similarly, informal waste pickers were approached, both in the city and at the landfill (see Section 4.4.2). Here, the language barrier was overcome with the help of accompanying people. Small shopkeepers were also quickly interviewed on the matter of single-use plastic ban (see Section 2.4).

3.1.3 Field Observations

In parallel, field observations were conducted in multiple areas across the municipality, including Essaouira's medina, Diabat, Ghazoua, Ouassane, and several beach zones. These site visits enabled the visual assessment of the general cleanliness (see Section 4.3), collection infrastructure, and differences between urban and rural waste conditions (see Section 4.2).

Finally, a visit to the Essaouira landfill was carried out in the company of a municipal official. The site visit allowed for the photographic documentation of the landfill's conditions and actual operations (see Section 4.4.1).

3.2 Analytical Tools for Diagnostic Phase

The analytical approach for the diagnostic phase was based on a set of KPIs selected through the literature review (see Section 2.5). These KPIs were chosen for their relevance to the context of Essaouira, particularly as a coastal, mid-sized, and tourism-dependent city, and were categorized under technical, environmental, institutional, financial, and social dimensions. They were summarized in Table 2 and 3.

Before applying these indicators in the diagnostic phase, it was necessary to establish clear assessment criteria for each KPI. This step involved defining qualitative or quantitative thresholds, based on literature, international standards, or contextual relevance, that allow the performance of each indicator to be systematically evaluated. These assessment rules will form the basis for measuring the current state of MSWM in Essaouira. That way we can quantify the city's performance across technical, financial, social, institutional, and environmental dimensions.

Each final indicator is rated on a scale of 1 to 3, which can be translated into a the following qualitative rating: *Good* (2.5–3), *Mediocre* (1.5–2.4), or *Poor* (<1.5).

Figure 7 is a schematic aid showing how inputs (literature, context, and data) are converted into 1–3 sub-indicator scores, weighted, and aggregated to a KPI value.

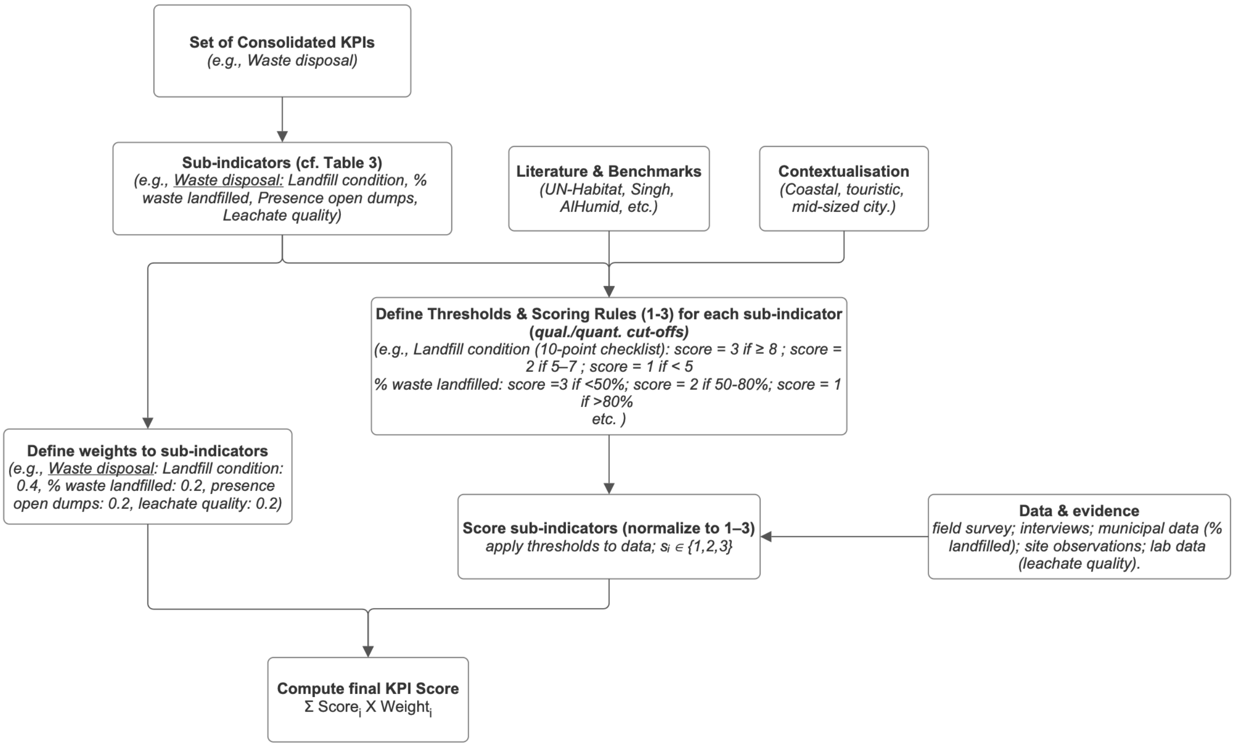


Figure 7: Visual summary of the KPI methodology from inputs to final score

3.2.1 Collection Efficiency

First, Collection Efficiency was assessed through five key sub-indicators: **collection coverage**, **frequency**, **waste separation at the source**, **general condition of waste containers**, and **citizen satisfaction concerning waste collection services**. For easier assessment, the collection coverage, frequency, and waste separation were combined into another sub-indicator called quality of service. The assessment for the sub-indicators are displayed in Tables 4 and 5.

The quality of collection services was evaluated based on the United Nations framework (UN-Habitat, 2025), which integrates service frequency, access to collection points (or door-to-door service), and the degree of waste separation.

Table 4: Scoring thresholds for Collection Service Quality

Score	Condition
3	Door-to-door or nearby collection point (within 200m), with regular weekly service and separation into three or more waste fractions
2	Same as above, but with separation into at least two fractions (e.g., wet/dry)
1.5	Door-to-door or nearby collection point with basic weekly service, without separation
1	Collection without weekly regularity, or access point >200m away
0	No collection service at all

In addition, thresholds from Singh et al. (2025) and AlHumid et al. (2019) were used to reinforce the requirement for minimum *coverage levels*. A service level could only be considered "3" or "2" if at least 90% of the population is covered. Scores were downgraded by one level if this threshold was not met.

The condition of bins was assessed based on survey observations of overflowing or damaged bins. While specific literature is lacking, thresholds were set based on logical acceptability.

Finally, citizen's satisfaction with waste collection services was measured through survey responses. AlHumid et al. (2019) consider high levels of satisfactions of 30-50% or more, moderate if 20–40% , and low if below 10-25%. However, these thresholds seem quite low, as they mean that a small 50% of the population being satisfied reflects a good waste collection. Therefore, more stringent thresholds were adopted in this study to align with broader public service evaluation practices (see Table 5)

Table 5: Scoring thresholds for Bin Condition and Citizen Satisfaction (Collection)

Sub-indicator	Score 3 (Good)	Score 2 (Moderate)	Score 1 (Poor)
Condition of bins	$<$15% bins in poor condition	15–30%	$>$30%
Citizen satisfaction	$\geq$70% satisfied	40–69%	$<$40%

The final **Collection Efficiency** score was calculated as a weighted average, assigning weights of 0.50 to the service quality score, 0.20 to the bin condition score, and 0.30 to citizen satisfaction. This distribution reflects the importance of social perception of collection services, especially in a highly touristic region.

3.2.2 Public Space Cleanliness

Public Cleanliness was assessed using four sub-indicators: **cleaning frequency**, **cleaning coverage**, **the presence of public bins**, and **citizen satisfaction with the cleanliness of public spaces**. The score assessment for each sub-indicator can be found in Table 6)

Cleaning frequency was assessed based on adjusted thresholds, taking into account the size and resources of the city. While Singh et al. (2025) define good performance as street sweeping conducted twice per day—based on practices observed in larger cities such as Nagpur, India, this standard was considered too demanding for a mid-sized city like Essaouira. Therefore, more context-appropriate thresholds were adopted.

Cleaning coverage evaluated the extent of public areas (e.g., streets, beaches, plazas) that receive regular sweeping. While Singh et al. (2025) define good performance as achieving coverage of at least 90% of public space, this threshold was once again adjusted to better reflect the urban structure and resource context of Essaouira, where wide coastal and peri-urban zone might be less prioritized.

The presence of public bins was evaluated based on field survey data and visual assessments.

Citizen satisfaction with public cleanliness was assessed through the local survey. The thresholds were defined similarly to those for satisfaction of waste collection.

Table 6: Scoring thresholds for Public Space Cleanliness sub-indicators

Sub-indicator	Score 3 (Good)	Score 2 (Moderate)	Score 1 (Poor)
Cleaning frequency	Daily or more	2–4 times/week	Once/week or less
Cleaning coverage	$\geq$80% public areas	50–79%	$<$50%
Public bin availability	High density (e.g. $<$100m)	Partial coverage	Minimal or none
Citizen satisfaction	$\geq$70% satisfied	40–69%	$<$40%

The final **Public Cleanliness** score was calculated as a weighted average: 0.25 for cleaning frequency, 0.25 for cleaning coverage, 0.20 for bin availability, and 0.30 for citizen satisfaction. This weighting reflects the importance of public perception in a tourism-driven city such as Essaouira, where visible cleanliness plays a key role in the urban experience and local economy.

3.2.3 Waste Generation Rate

The **Waste Generation Rate** indicator measures the average quantity of MSW generated per person per day, expressed in kilograms per capita per day (kg/capita/day). This metric reflects both consumption behaviors and the level of pressure placed on local waste management systems.

Worldwide, the average waste generation rate is estimated at 0.74 kg/capita/day (Kaza et al., 2018), while the Middle East and North Africa (MENA) region averages slightly higher at 0.81 kg/capita/day. According to reports from the European Commission, urban areas in Morocco generate an average of 0.76 kg/capita/day in 2019 (Diaco et al., 2020). However, more touristic and densely populated cities such as Marrakech have reported significantly higher rates, reaching up to 1.12 kg/capita/day in 2015 (Campitelli et al., 2023). In European coastal destinations, which combine high tourism pressure with high-income consumption patterns, rates can exceed these values. For example, the island of Sardinia in Italy has an average of 1.214 kg/capita/day (Bortolato, 2022).

Given these benchmarks, the thresholds from Table 7 were defined to assess Essaouira's waste generation rate.

Table 7: Scoring thresholds for Waste Generation Rate

Score	**Waste Generation (kg/capita/day)**	**Interpretation**
3	<0.75	Reflects efficient consumption or strong prevention practices
2	0.75–1.0	In line with national or regional urban averages
1	>1.0	Indicative of high consumption or seasonal tourism pressure

Although higher waste generation does not necessarily imply poor management performance, it highlights the need for reinforced waste prevention strategies and resilient collection and treatment systems, particularly in tourism-driven cities such as Essaouira.

3.2.4 Waste Recovery

Waste Recovery was assessed through three sub-indicators: **the existence of household-level waste separation**, **the actual recycling rate achieved in the city**, and **the presence of a functional MRF**. While waste separation and MRF presence are binary indicators, the recycling rate is a quantitative, outcome-based measure. All three were normalized to a 1–3 scoring scale for consistency.

Waste separation at source was evaluated based on whether households in Essaouira practice source separation.

Recycling rate was defined as the share of total municipal solid waste that is recycled, either through formal systems or informal recovery channels. The thresholds were based on national and regional benchmarking of the PNDM.

The presence of an MRF was assessed based on whether such a facility exists and is functional within the municipal waste system.

Table 8: Scoring thresholds for Waste Recovery sub-indicators

Sub-indicator	**Score 3 (Good)**	**Score 2 (Moderate)**	**Score 1 (Poor)**
Waste separation at source	Practiced		Not practiced
Recycling rate	≥15%	5–14%	<5%
Presence of MRF	Exists and functional		Does not exist

The final Waste Recovery score was calculated as a weighted average, with weights of 0.4 assigned to both waste separation and recycling rate, and 0.2 to MRF presence. This reflects the relative importance of behavioral practices and actual recovery outcomes, while acknowledging the role of recovery infrastructure.

3.2.5 Waste Disposal

This KPI assesses the environmental performance and operational condition of final disposal activities in Essaouira. It includes four sub-indicators: **landfill condition**, **the percentage of waste landfilled**, **the presence of uncontrolled dumping**, and **leachate quality**.

Landfill condition was evaluated using a 10-point checklist inspired from the UN-Habitat (2025) ladder of control. Each criterion received 1 point if observed or confirmed during the site visit, and 0 if not. The full list of criteria is provided in Table 9.

Table 9: Landfill condition checklist used for scoring operational and environmental performance

#	**Criterion**
1	Waste is compacted regularly
2	Waste is covered with soil or inert material at least once per week
3	Perimeter fencing or boundary wall is present to limit access and wind-blown waste
4	A leachate collection system is present and operational
5	A gas collection system is present and operational
6	The site is correctly staffed
7	Waste is weighed or registered (e.g., entry logs, weighbridge)
8	Provisions are made for workers' health and safety
9	Bulldozer or heavy equipment is present and operational on site
10	Access roads are in good condition and allow truck movement even in wet conditions
	Total Score (/10)

Percentage of waste landfilled was assessed as the share of total MSW ending up in landfill or dumping sites. Thresholds were adapted from Singh et al. (2025) but contextualized to Essaouira.

The presence of open dumps was based on field observations and interviews.

The leachate quality score was derived from two sub-indicators: Chemical Oxygen Demand (COD, in mg/L) and the BOD/COD ratio. Each one was scored individually on a scale from 1 to 3, with thresholds defined based on benchmarks from AlHumid et al. (2019). The final score was calculated as the average of the two sub-scores, in order to ensures a balanced evaluation of pollution intensity and biodegradability.

Table 10: Scoring thresholds for Waste Disposal sub-indicators

Sub-indicator	**Score 3 (Good)**	**Score 2 (Moderate)**	**Score 1 (Poor)**
Landfill condition (score/10)	8–10	5–7	<5
% of waste landfilled	<50%	50–80%	>80%
Presence of open dumps	None observed		Some observed
Leachate COD (mg/L)	<8,000	8,000–13,000	>13,000
BOD/COD ratio	>0.4	0.3–0.4	<0.3

The final **Waste Disposal** score was calculated as a weighted average: 0.4 for landfill condition, 0.2 for percentage of waste landfilled, 0.2 for presence of open dumps, and 0.2 for leachate quality.

3.2.6 Financial Sustainability

The Financial Sustainability indicator was measured through two sub-indicators: **the MSWM expenditure per capita**, and **the Recyclable Market Value (RMV)**. The assessment criteria for each indicator can be found in Table 11. The thresholds for expenditure were defined based on global benchmarks from the World Bank's *What a Waste 2.0* report (2018), and converted to MAD. These thresholds aim to reflect levels of service and long-term financial viability. RMV thresholds were found in Singh et al. (2025). However, they seemed way too high, with values like 3.5 MAD/kilo of waste considered as "low". New thresholds were thus crated for the purposes of this study.

Table 11: Scoring thresholds for Financial Sustainability: MSWM Expenditure per Capita

Sub-indicator	**Score 3 (Good)**	**Score 2 (Moderate)**	**Score 1 (Poor)**
MSWM expenditure per capita (USD/year)	Exceeds \$896 per capita; strong financial sustainability with likely full coverage, treatment, and cost recovery mechanisms	Between \$269 and \$896 per capita; moderate sustainability, basic services in place but may lack full treatment or stable financing	Below \$269 per capita; underfunded system with poor coverage, unmanaged disposal, and limited infrastructure
Recyclable Market Value (RMV) (EUR/kg)	Above 0.8 MAD/kg	Between 0.35 and 0.8 MAD/kg	Below 0.35 MAD/kg

3.2.7 Public Engagement

The indicator of public engagement was evaluated as a single indicator of **Public participation** and was assessed according to Table 12.

Table 12: Scoring thresholds for Public Participation

Score	Condition
3	Citizens actively participate in clean-up actions, awareness events, and are involved in planning or feedback processes; programs exist and are well attended
2	Some programs exist (e.g., school campaigns, clean-up days), but public engagement is limited or sporadic
1	Little or no public involvement observed; waste initiatives are carried out with minimal citizen input

3.2.8 Informal Sector Role

The role of informal sector was composed of the following two sub-indicators: **Informal waste pickers presence** and **Informal sector integration**. Their evaluation is described in Table 13.

Table 13: Scoring thresholds for Informal Sector Role sub-indicators

Sub-indicator	Score 3 (Good)	Score 2 (Moderate)	Score 1 (Poor)
Informal waste pickers presence	Clearly present and actively involved in collection, sorting, or recovery at multiple points (e.g., landfill, streets)	Present but marginal, inconsistent, or limited to specific locations	Rare, not visibly active, or no reliable evidence of presence
Informal sector integration	Formally recognized or supported (e.g., contracted, given equipment, included in MSWM plans)	Some informal coordination or NGO-led engagement	Not recognized or supported by municipality or MSWM contractor

The final **Informal Sector Role** score was calculated as a simple average of the two sub-indicators, with equal weights of 50% for the presence of informal waste pickers and 50% for their integration. This approach reflects the equal importance of both actual involvement and institutional recognition in assessing the informal sector's role.

3.2.9 Institutional Framework

Finally, the institutional framework was evaluated through three sub-indicators: **the existence of a municipal waste plan**, **plastic and litter regulation**, and **environmental oversight and citizen access**. They were assessed based on Table 14.

Table 14: Scoring thresholds for Institutional Framework sub-indicators

Sub-indicator	Score 3 (Good)	Score 2 (Moderate)	Score 1 (Poor)
Existence of municipal waste plan	Official municipal waste plan exists		No local waste plan exists
Plastic and litter regulation	Local enforcement of bans or fines on littering/plastics with active follow-up	Legislation exists but weakly enforced	No legislation or enforcement observed
Environmental oversight and citizen access	Functional municipal body exists to monitor MSWM and receive citizen complaints	Body exists but inactive or limited citizen access	No oversight or complaint mechanism in place

The final **Institutional Framework** score was calculated as a weighted average of the three sub-indicators: 30% for the existence of a municipal waste plan, and 35% each for plastic and litter regulation, and environmental oversight and citizen access. This weighting prioritizes regulatory enforcement and citizen accountability while still recognizing the importance of strategic planning.

3.3 Methodology for Strategic Recommendations

The strategic phase of this thesis builds on the diagnostic assessment to develop a set of recommendations for improving MSWM in Essaouira. The approach combined **strategic planning** with **practical engineering analysis**, ensuring that proposals address both systemic and operational gaps.

Sources of inspiration came from best practices from developed countries, as these contexts offer functioning, integrated waste management systems with clear institutional frameworks, advanced infrastructure, and proven environmental performance. While waste characteristics in developed countries differ—particularly due to lower organic content—alternative benchmarks from countries with similar compositions were limited. Most of these countries face similar or greater systemic challenges, reducing their suitability as primary references. Fieldwork observations, stakeholder interviews, prior coursework in environmental engineering, and informal consultations with faculty members were therefore used to complement international lessons and contextualize them for Essaouira.

The **analytical approach** followed a sequential process linking the diagnostic findings to actionable strategies. First, weaknesses identified in the diagnostic phase were mapped against the functional pillars of a waste management system: collection, separation, treatment, disposal, and governance. Second, each pillar was cross-referenced with international good practices to identify adaptable interventions and prioritize those offering the highest environmental and institutional benefit. Third, the proposed actions were screened for feasibility in Essaouira's context—considering existing infrastructure, municipal capacity, public behavior, and financial constraints. This iterative process allowed the recommendations to evolve from broad principles into a phased roadmap combining short-term pilots with longer-term structural reforms.

The inclusion of an **engineering component** aimed to reinforce the technical realism of the strategic proposals. Specific design-oriented recommendations were developed for key operational areas such as leachate management, landfill capping and gas control, and future treatment technologies. These relied on site observations, and engineering principles derived from established technical literature and IPCC guidelines. Where possible, indicative calculations and performance estimates were produced to illustrate potential environmental gains (e.g., avoided methane emissions). This integration ensured that the strategic framework is supported by technically sound and quantifiable options, bridging the gap between policy planning and on-the-ground implementation.

In terms of tourism considerations, although Essaouira is a major tourist destination, fieldwork confirmed that seasonal adaptations in collection and cleaning already mitigate tourism-related peaks. Consequently, the recommendations focus on strengthening year-round operations, suitable for tourism peak volumes, rather than designing tourism-specific measures.

4 Diagnostic Phase — Evaluation of the MSWM System in Essaouira

This section presents a diagnostic analysis of the MSWM system in Essaouira, grounded in qualitative and quantitative findings from the fieldwork conducted in april 2025. Through site visits, stakeholder interviews, and document analysis, the aim is to assess the current performance of waste generation, collection, treatment, and disposal practices in the city. While national legislation and programs have promoted the modernization of MSWM across Morocco, Essaouira's system remains characterized by no waste separation and heavy reliance on landfilling. The municipality allocates approximately 28 million MAD to MSWM annually, representing about 20% of its total annual budget, therefore highlighting the sector's weight in local governance. This funding comes from a mix of sources, including local taxes, as well as intergovernmental transfers. Notably, a share of the national Value Added Tax is redistributed to municipalities according to criteria such as population size, which helps support essential services like waste management. The following sections diagnose the main operational and structural aspects of Essaouira's MSWM system to identify gaps and inform future planning.

4.1 Waste Generation

Understanding the patterns and quantities of waste generation is essential to designing effective and sustainable MSWM systems. Literature review on waste generation in Essaouira (see Section 2.3.1) indicated that the city was experiencing increasing quantities of solid waste due to urbanization, tourism, and population growth, with an average of 65 tons of waste generated per day, over the years studied, which ended in 2014. The review also showed the composition of waste in Essaouira, highlighting an important fraction of organic waste (60-70%) present in the waste stream. Plastic followed with 9%, then cardboard with around 5%. Hazardous waste was also found to represent around 2% of the total waste generated and ending up in landfills.

According to the 2017 Provincial Director Plan for Municipal Solid Waste Management (Plan Directeur Provincial de Gestion des Déchets Ménagers et Assimilés, PDGDM) for the Essaouira Province, which could not be found on internet but was provided to us by the municipality, the urban municipality of Essaouira generated approximately 71 tons of MSW per day at the time of the study. The PDGDM projected a moderate increase in waste generation rates over the following decade, based on a growth rate mentioned in national statistics. Their 2035 waste generation was estimated at 81.4 tons/day. However, these projections dated from 2014, and predicted 68.5 tons of waste generated per day in 2020, an amount which had already been exceeded in 2017, according to their own information.

This forecast does not appear very consistent with current estimates provided by municipal authorities and other stakeholders interviewed. The municipality itself does not track waste quantities continuously and only relies on national or academic studies for such data. However, during the fieldwork conducted in 2025, local officials and many stakeholders reported that the commune currently produces around 85 tons of waste per day during the low season, increasing by 30% to approximately 110 tons during peak summer months, from June to August/September. This confirms the significant seasonal effect driven by tourism, which inflates both the population and waste generation temporarily. It also suggests a strongly higher-than-anticipated increase since the 2017 projections, with an actual 30% waste generation increase in 10 years compared to a projected 28% increase over 20 years. (see Figure 8).

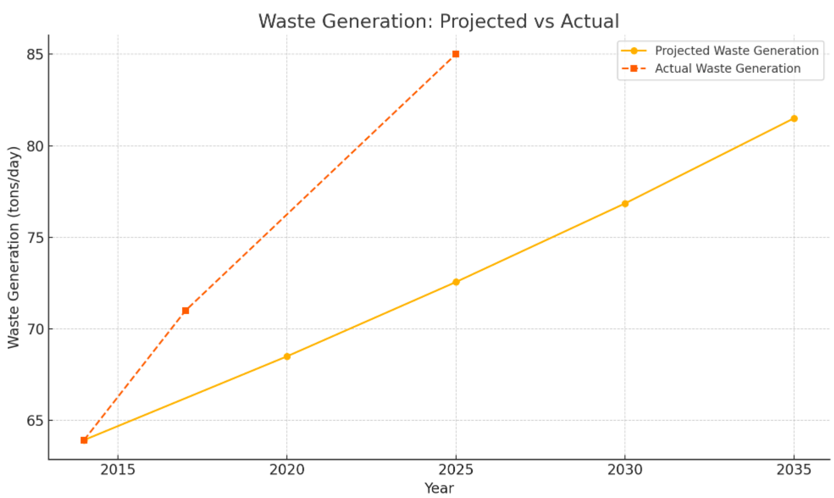


Figure 8: Projected vs actual municipal solid waste generation in Essaouira (2014–2035)

Overall, it is important to note that there is however no systematic or continuous monitoring of waste generation in Essaouira. The figures mentioned above rely largely on estimates provided by municipal authorities, previous planning documents, or isolated national studies. Furthermore, other factors complicate waste accounting, such as the presence of black spots (illegal dumpings) not taken into account, the presence of the informal sector collecting waste, or neighbouring municipalities throwing their waste in Essaouira because of the lack of infrastructure in their own territories (see Sections 4.2). Moreover, no difference is made between residential, commercial, or touristic waste sources, which limits the ability to effectively plan and adapt MSWM strategies to the city's evolving needs.

4.2 Waste Collection

Once generated, municipal solid waste must be efficiently collected to prevent environmental pollution, safeguard public health, and ensure proper downstream treatment. According to Law 113-14, as discussed in Section 2.4, the responsibility for MSWM lies with the local municipality. In Essaouira, the municipality opted for a delegated management approach, governed by Law 54-05, which establishes the legal framework for outsourcing public services to private operators. Under this system, the municipality launches a public call for tenders that includes a detailed technical and financial dossier outlining service requirements, operational standards, infrastructure and investment needs, and expected performance levels. Interested companies submit proposals, which are evaluated by the municipality based on both technical quality and cost-effectiveness. Once a company is selected, the proposed contract and service plan must be submitted for validation by the Ministry of Interior and the Ministry of Environment before implementation. In Essaouira, the company ARMA was ultimately selected as the delegated operator under a seven-year contract. Their responsibility covers the four following main activities:

- The collection of household and similar waste (frequency, locations, etc. determined by the municipality)
- Manual street sweeping
- Mechanical street sweeping
- Cleaning of the four beaches (Essaouira, Diabat, Ouassane, Assafi)

ARMA's performance are monitored and tracked through daily, monthly, and yearly reports of their activities. The municipality's delegated management council is responsible for checking whether performances, staff levels, investments, etc. are met. Cuurently, the company employs 176 workers for its collection and cleaning activities.

Now let us dive into the operations. First and foremost, it is important to underline that waste separation at the source does not exist in the MSWM system of Essaouira. Waste is disposed of unsorted in communal containers (see Figure 9), and there is little to no infrastructure or institutional support for selective collection in the city. Moreover, the cultural behaviour for waste management in Morocco is generally very poor, which means that separating waste remains rare a poorly institutionalized. An early effort to introduce source separation was launched in 2001 through a Cleanliness Convention at Essaouira, which piloted selective sorting projects in a few neighborhoods. Unfortunately, the initiative failed to be properly introduced due to the shortcomings of the implementing company and lack of long-term planning.

Figure 9: Unsorted waste in a communal container in Essaouira

The only recurring exception to the absence of separate bins is a seasonal campaign led by the Agence Nationale des Ports (ANP), which sponsors a waste separation initiative on Essaouira's main beach during the summer months, as part of the Blue Flag certification program. Color-coded bins are installed for different waste types, especially plastics (see Figure 10a). Yet, field observations and stakeholder interviews confirm that the separation is not respected in practice, with mixed waste frequently discarded in all bins (see Figure 10a and Figure 10b) and no clear monitoring or evaluation of the initiative's effectiveness.

(a) Color-coded bins placed on the beach by ANP

(b) Separated bin with overflowing mixed waste

Figure 10: Color-coded waste separation bins installed by ANP on Essaouira beach

In parallel, a small number of private households and hospitality establishments—particularly hotels—have begun separating part of their waste voluntarily. This sorted waste is often collected not by ARMA, but by informal actors and companies, such as TRIVALDEC, who recovers recyclable materials like plastics, metals or cardboards. These decentralized efforts remain marginal and are not officially supported or integrated into the city's MSWM strategy, but they do demonstrate some local potential for future circular economy initiatives.

As for the normal waste collection, it is primarily carried out using a communal container system (see Figure 11). Residents are expected to dispose of their waste in shared bins located throughout the city, from which ARMA collects the waste according to a predefined schedule. The collection is performed day and night, by a fleet of workers and vehicles adapted to the specific needs of different urban contexts, such as the narrow alleys of the Medina (see Figure 12a and Figure 12b). The frequency of collection varies by zone, depending on population density, commercial activity, and touristic pressure.

Figure 11: Communal waste containers in Essaouira

(a) ARMA waste collector handling household waste in Essaouira's city center at night

(b) Adapted-sized collection vehicle used by ARMA in the Medina

Figure 12: Examples of ARMA's adapted collection operations

While delegated management of MSWM in Essaouira has established a structured framework for service provision, the actual performance of the collection system varies depending on the area. Interviews with the municipality indicated that waste collection works relatively well in urban zones, particularly within the city of Essaouira and the adjoining urbanized extension known as Ghazoua (often referred to as "New Essaouira"), and they affirm a 100% collection rate in the municipality. These areas benefit from higher population density, greater visibility, and the logistical prioritization of collection routes. However, despite high collection frequencies in these areas, survey responses reveal that a majority of residents still consider the collection insufficient. In Ghazoua, for example, 75% of respondents acknowledge the presence of enough collection bins. Yet only over 30% rate the overall service positively, and 25% consider the collection frequency adequate. This dissatisfaction—even in zones where waste is collected every day—points to qualitative issues rather than a lack of collection events per se. More than 60% of respondents to the survey also indicated that communal containers were generally damaged or overflowing. Interviewees mentioned dirty and smelly bins as well, and noted that collection schedules were not always synchronized with the rhythm of waste generation.

More critically, semi-rural and rural areas under Essaouira's jurisdiction experience visibly poorer collection services. While collection does occur, bins are often in bad physical condition and respondents from peripheral areas frequently report insufficient bin availability, dirty areas around bins, and irregular collection, all of this attracting stray animals and others (see Figure 13). The municipality attributes part of these shortcomings in collection to the lower volume of waste generated per capita in rural areas, arguing that residents consume fewer packaged goods and manage a larger share of organic waste through reuse, composting, or feeding livestock. As such, fewer containers and lower collection frequency are deemed "sufficient" by municipal standards. The other part of the deficiency is explained otherwise. Neighbouring municipalities, like the one of Sidi Kaouki, do not have any waste collection systems of their own. These municipalities lack both infrastructure and delegated operators, and as a result, their residents often resort to dumping their waste in Essaouira's bins. This occurs notably in bordering villages like Ouassane, which hosts only a few hundred inhabitants but receives a disproportionate amount of waste due to inflows from adjacent territories. Ghazoua, with its higher number of bins and proximity with other municipalities, also suffers from a similar situation. The result is a thus misalignment between container allocation and actual waste generation. The number and location of containers were defined based on Essaouira's official population (~82,000 residents, ~640 hab/km^2 (City Population, 2024)), but the user base extends beyond municipal boundaries. This inflow overloads the system, especially in southern and peripheral zones.

Figure 13: Communal waste containers in Ouassane, Essaouira

Crucially, there is no formal collaboration between Essaouira and its neighbouring municipalities on the issue of MSW collection. While Essaouira remains the only sizable urban municipality in the area (compared to neighbouring communes with population densities <70 hab/km^2 (City Population, 2024)), no intermunicipal agreements or cost-sharing mechanisms exist.

Concerning waste collection, it is also important to note that Law 113-14, which governs MSWM in Morocco, applies exclusively to waste generated by households. As such, waste produced by private businesses, restaurants, hotels, and other non-household and non-public actors is not included in the municipal collection service provided by ARMA. These entities are required to independently contract private waste collectors to manage their waste. On the one hand, this can foster positive practices, such as partnerships with collectors like TRIVALDEC, previously mentioned, who collects separated waste from hotels, businesses, or individuals. On the other hand, this can also lead to significant risks of moral hazard. Some businesses may sign contracts with unregulated or pseudo-collectors who, in the absence of enforcement, dispose of the collected waste in unauthorized locations, such as open fields, rather than transferring it to the official landfill, making it cheaper and more convenient for them. Alternatively, some commercial actors choose to enter tripartite contracts with the municipality, allowing ARMA to collect their waste. This service is however not free of charge, unlike the collection provided to residential households. In light of these challenges, a promising initiative is currently being developed through a partnership between the University of Rostock and Cadi Ayyad University. The project, known as TouMaLi, is being piloted in Ghazoua and focuses specifically on waste generated by the tourism sector. Recognizing the importance of this separately managed waste stream, TouMaLi aims to establish a dedicated center for the collection, separation, and valorization of tourism-related waste.

Overall, despite efforts to contain municipal waste within the formal collection system, numerous black spots (or wild dumps) appear throughout the municipality and its surrounding (see Figure 14). These uncontrolled waste disposal sites emerge primarily in zones with limited oversight or infrastructure, often near roadsides, or behind public housing clusters. They represent a significant gap in the city's waste collection framework and undermine broader cleanliness and environmental objectives. One particularly illustrative example of this phenomenon is the green belt area, located at the administrative boundary between Essaouira urban municipality and the national domain of Water and Forestry. This area (see Figures 15 and 16) clearly shows a contrast with the side managed by the municipality being relatively clean, with regular containers and visible collection, while the opposite side, falling under the responsibility of the Water and Forestry domain, is heavily littered with waste. Interviews revealed that this discrepancy results from an administrative division of responsibility. The municipality's contract with ARMA stops at the border, and beyond that line, waste management becomes the responsibility of national forestry services. Although municipal officials reported that they attempt to encourage ARMA to extend cleaning efforts into this area, staff members from ARMA indicated that they have never actually been instructed or resourced to collect there. This case illustrates a broader governance issue. Territorial and institutional fragmentation leads to neglected zones where no entity takes operational responsibility. The green belt, as a transition zone between urban and natural land, is particularly vulnerable to illegal dumping, and the lack of coordination between municipal services and national agencies allows such situations to persist.

The first image of Figure 14 shows a wild dumpsite directly bordering the sea, in clear violation of the Littoral

Protection Law (Law 81-12), which prohibits waste disposal within 100 meters of the coastline. This situation also highlights the need for better enforcement mechanisms to protect coastal ecosystems from unmanaged solid waste.

Figure 14: Open dumps in Essaouira and its surroundings.

Figure 15: Green belt area contrast between clean and dirty side

Figure 16: Green belt wild dumps (Water and Forestry National Domain)

Outside of these jurisdictional grey areas, wild dumps that fall within the municipal perimeter are in theory meant to be handled by ARMA. When reported or observed, ARMA is expected to intervene and clean these areas. However, both ARMA representatives and municipal staff acknowledged that traceability and monitoring of these sites remains a challenge, as there is no systematic mapping of wild dumps. To improve responsiveness, the municipality has discussed the development of a digital platform or app, and a "green line" (telephone hotline), allowing residents to report wild dumps directly to the responsible services. This system, if implemented, could significantly enhance public participation, spatial monitoring, and intervention speed. For now, however, such tools remain at the planning stage.

4.3 Public Cleaning

As explained in Section 4.2, the responsibilities of the delegated operator ARMA extend beyond household waste collection to include a range of public cleaning services. These include manual and mechanical street sweeping, and the maintenance of Essaouira's four main beaches (Essaouira, Diabat, Ouassane, and Assafi). These operations are essential not only for maintaining hygiene in shared urban spaces, but also for preserving the city's appeal as a national and international tourist destination. One of the most significant challenges facing public cleaning efforts in Essaouira is the city's climate, particularly its persistent high winds, blowing from the North-East, and reaching speeds up to more than 12m/s in summer. During that season, 35% of wind speeds are between 8 and 12m/s, while 43% are between 4 and 8m/s (PDGDM, 2017). Indeed, Essaouira is ranked as one of the windiest cities in Morocco (Nfaoui et al., 1998). Therefore, these conditions contribute heavily to the scattering of litter, sand, and organic debris.

4.3.1 Manual and Mechanical Sweeping

Street sweeping operations—whether manual or mechanical—aim to mitigate the effects mentioned above. Manual sweeping typically involves ARMA staff removing sand, debris, and stray waste from sidewalks and road edges using brooms and mobile collection bins (see Figures 17a and 17b). Mechanical sweeping, meanwhile, is carried out using adapted vehicles that can navigate the city's narrow alleyways, including those of the Medina (see Figure 17c). According to the municipality, the manual cleaning is done everyday, over the entire territory, with 3km covered for each worker each day.

(a) Manual sweeping of sand

(b) Manual sweeping and collecting of waste

(c) Mechanical sweeping in the medina

Figure 17: Examples of manual and mechanical street sweeping in Essaouira

Although streets and public spaces looked quite clean (at the exception of areas with dumps) from the eye of a visitor, survey results indicate that satisfaction with public cleaning services remains low. Over 70% of respondents expressed dissatisfaction, citing issues such as dirty streets, unpleasant odors, and the persistent presence of informal dumps. Notably, stray animals were mentioned in 70% of responses, often linked to spilled waste and poor bin maintenance. In contrast, only approximately 10% of respondents reported having no concerns or problems about the cleanliness of public spaces in their area.

This widespread dissatisfaction may partially reflect a mismatch between the number of cleaning staff assigned per neighborhood and the surface area or waste load to be managed.

Furthermore, informal discussions with ARMA personnel revealed possible morale and motivation issues within the workforce. Several collectors expressed a clear preference for the former service provider, *Ozone*, citing better working conditions under the previous contract. Although their remarks were anecdotal, this sentiment raises questions about employee satisfaction and operational discipline, both of which may influence the consistency and quality of public cleaning. If workers lack incentives or do not feel engaged in their roles, even well-structured cleaning schedules may fail to produce visibly clean outcomes in practice.

Additionally, interviewees frequently mentioned the near-total absence of public litter bins throughout the city, which likely contributes to littering and reduces the effectiveness of daily cleaning efforts. Some public bins were reported and seen along the dike bordering the main beach promenade, and in some neighbourhood in Ghazoua and essaouira.

4.3.2 Cleaning of Beaches

In addition to street cleaning, ARMA is responsible for maintaining the cleanliness of Essaouira's beaches. These cleanings occur everyday during the summer period, and once a month during the winter period. Interviews with workers revealed that plastic waste such as bottles, bottles caps, and plastic bags were the most common type of waste found on the beaches, followed by cigarette butts, and remnants of fishing nets. During the summer months, their effort is boosted by the ANP, which organizes seasonal campaigns that include the deployment of additional cleaning personnel and machinery (see Figure 18), in addition to the color-coded separate bins mentioned earlier (see Figure 10).
As for classic public bins, they are present all year long along the beach promenade, but no bin is actually installed on the sand.

Figure 18: Collection machinery sponsored by ANP

Further support for beach cleaning comes from civil society and private sector initiatives. Environmental NGOs like Surfrider Foundation occasionally organize beach clean-up events aimed at raising public awareness about marine pollution. Similarly, companies such as MIKA engage in plastic waste collection on the beach, which is subsequently recycled, contributing to local circular economy efforts (see Figure 19).

Figure 19: Beach cleaning organized by Surfrider and MIKA (2024)

All of these combined efforts have contributed to Essaouira beach being awarded the "Pavillon Bleu" (Blue Flag) label for the 20th consecutive year in 2024. This certification, granted by the Mohammed VI Foundation for Environmental Protection in collaboration with the Foundation for Environmental Education (FEE), recognizes beaches that meet high standards in water quality, environmental education, safety, and management. To maintain this label, the beach undergoes rigorous monitoring during the summer season. Water quality is tested biweekly, and sand quality is assessed twice per season. The results of these tests are publicly displayed on information boards along the beach, ensuring transparency and keeping both residents and visitors informed (see Figure 20).

Figure 20: Billboard with beach plan, information, and water quality results

However, despite these institutional and community-led initiatives, waste accumulation remains an issue further along the coastline. Strong winds and ocean currents, particularly those originating near Essaouira's port, tend to carry floating debris and plastic waste southwards, sometimes as far as Sidi Kaouki (a coastal commune which, as previously mentioned, does not even have a waste management system). These hydrodynamic factors make beach cleanliness difficult to maintain beyond the immediate vicinity of the central beach. Moreover, the additional bins installed along the dike during the summer months are not sufficient to prevent visitors from discarding waste directly onto the sand. According to the beach director, although littering is formally prohibited, enforcement remains limited. Individuals are sometimes verbally reprimanded for littering, but no fines are issued in practice. This lack of deterrence, combined with persistent behavioral norms, continues littering practices and undermines the overall cleanliness of the beach environment.

4.4 Waste Treatment and Disposal

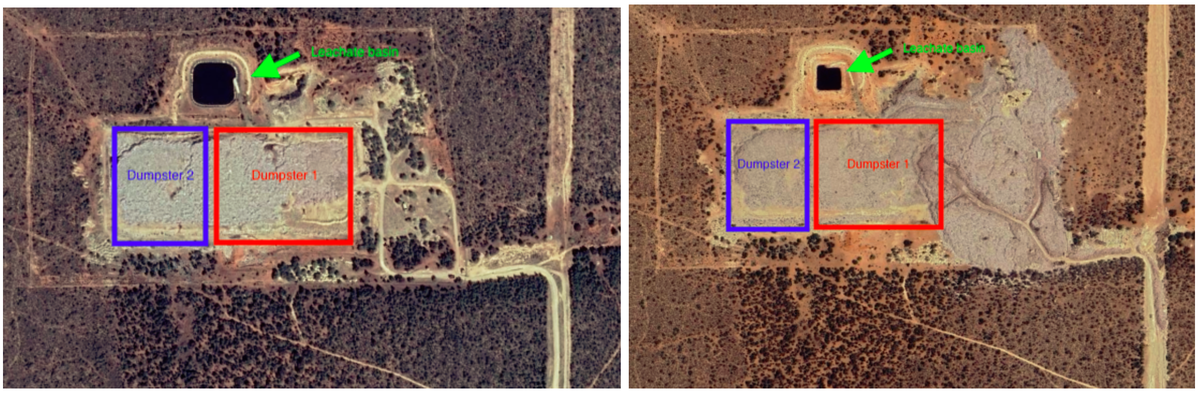
Once collected, municipal solid waste in Essaouira is transported by truck to the city's controlled landfill. A few years back, part of the waste was brought to an open dump, 1 kilometer from the South entry of Essaouira. It has since rehabilitated by covering up the waste and closing the site. Unfortunately, no data on the quantities, volumes or else are available concerning this dump. A previous study by Wiechert et al. (2025) referenced the existence of a transfer station operating as an intermediary between collection points and the landfill. However, fieldwork conducted during this study confirmed that the transfer station is no longer functional and has been permanently closed. Because waste is neither separated at the source or after during collection, it arrives mixed at the landfill. Except for recovery by the informal sector (covered in Section 4.4.2), no recycling or recovery processes are implemented. As a result, the totality of municipal waste is disposed of directly at the landfill site.

4.4.1 Essaouira's Controlled Landfill

As outlined in Section 2.3.2, the Essaouira landfill was the first engineered landfill in Morocco, inaugurated in 2001 and designed as a Class 1 site for non-hazardous waste. The landfill is supposed to feature a geomembrane liner, leachate drainage and evaporation systems, and access infrastructure. The waste is supposedly compacted, buried, and covered with soil. The site was projected to operate for 10 to 18 years, depending on future expansion, receiving around 65 tons of waste daily (Chiguer et al., 2016; Zalaghi et al., 2019).

However, after several interviews with different stakeholders from the MSWM system in Essaouira, it became quite clear that the controlled landfill was not as controlled as it was supposed to be. The Chief of the Technical Division of the Municipality referred to the landfill as a "failure". The company who supported the municipality in drafting the original call for tenders puts partial blame of this failure on the original winning contractor, GMF, citing their inadequate capacity to manage the site according to required standards. They also criticized the municipality's selection process, suggesting that the choice of operator contributed to the site's long-term dysfunction. Currently, the municipality indicated that no company is officially appointed to manage the landfill. In the interim, ARMA, the company responsible for waste collection, is overseeing basic operations at the site while awaiting a formal reassignment of responsibilities. According to municipal representatives, a new operator will eventually be designated as part of a broader rehabilitation and upgrade project for the landfill. However, the implementation of this project remains delayed, as the proposed plans are still pending approval from national authorities. This will be covered later in this section. As a result, management of the landfill has been minimal, with little oversight or structured operations in the meantime. And to clarify the nature and the extend of the term "failure," a site visit was conducted.

First of all, compared to previous studies from 2016, the current volume of incoming waste has increased. Today, the landfill receives approximately 15 to 20 trucks per day, carrying an estimated 85 tons of waste from Essaouira municipality alone (80-85% of all waste directed to the landfill), along with smaller, irregular quantities from neighbouring communes in the province of Essaouira. This evolution is clearly visible in satellite imagery, which illustrates the landfill's expansion over time (see Figures 21a and 21b). Figure 21a presents the site in 2016, at a time when operational structures, access roads, and waste cells were still relatively clearly delineated. Figure 21b, captured in 2023, shows substantial growth in the occupied surface area and volume of waste, with new dumping zones extending way beyond the previously defined perimeter. During the field visit, it was observed that waste now accumulates even at the entrance of the landfill (see Figure 22). According to the official municipal site development plans, disposal operations should currently be taking place in the dumpster 2, located at the West of the site (see Figure 21b). However, direct observations revealed that the majority of waste is in fact being deposited in the eastern and northern parts of the landfill, at the end of the visible "pathways." This practice deviates from the intended waste management layout and likely exacerbates both leachate and spatial planning issues.



(a) Essaouira's landfill, skyview 2016 (Source: Google Earth

(b) Essaouira's landfill, skyview 2023 (Source: Google Earth

Figure 21: Skyview of Essaouira's landfill over time

Figure 22: Entrance of the landfill where waste accumulates

Upon arrival at the site, field observations quickly confirmed the stark contrast between the landfill's intended operational design and its current state. Only four workers were present at the site: one guarding the entrance and two to three managing waste disposal. Equipped with two bulldozers, they appeared primarily tasked with redistributing the incoming waste from the 15 to 20 trucks arriving daily. However, no proper compaction or soil covering was taking place. Instead, waste was merely pushed into large mounds, creating expansive "mountains" of trash that extended far across the site, giving the impression of uncontrolled dumping (see Figure 23). The original staff cabins installed on-site for operational use appeared entirely abandoned and are now partially buried under waste, highlighting the lack of functional infrastructure and on-site oversight (see Figure 24).

Figure 23: Waste accumulation creating mountains extending across the site

Figure 24: Workers cabin being swallowed by waste

The consequences of this mismanagement were immediately apparent. The absence of compaction and regular covering creates a very strong, unpleasant smell, and the overall hygiene conditions at the site are very poor. The uncovered waste attracted numerous birds and seagulls, which feed and rest directly on the trash. The lack of fencing, a basic component of sanitary landfills, enabled further hazards. Notably, a shepherd was observed walking his flock directly through the landfill, where sheeps and goats were seen feeding on exposed waste, highlighting the public health risks for both animals and humans (see Figure 25). Strong coastal winds scattered light waste, especially plastic bags, throughout the surrounding area, severely polluting the adjacent forest (see Figure 26).

Figure 25: Sheep flock feeding on piles of waste in the landfill

Figure 26: Adjacent forest polluted by waste from the landfill

In addition to the formal workforce, although supposedly forbidden, a large number of informal waste pickers were operating actively at the site. Previous interviews with stakeholders estimated their number to be around 20 in total. Remarkably, some had even constructed makeshift huts within the landfill itself, in the middle of the waste, where they stored and sorted valuable items retrieved from the waste (see Figure 27). This also raises serious concerns regarding occupational safety and human dignity, especially given the unsanitary and uncontrolled conditions in which these individuals live and work. Additionally, interviews with external stakeholders revealed that, while private clinics do take care of their hazardous waste, the public hospital of Essaouira does not. Apparently, their waste is discarded similarly as normal municipal waste, therefore ending up in the landfill, and worsening its condition, confirming what was seen in literature review (see Section 2.3.1).

Figure 27: Infomal waste pickers hut and loot

Equally troubling was the state of the landfill's leachate basin, a critical component designed to contain and manage toxic liquid runoff. The basin was visibly contaminated with wind-blown waste, including plastic, other debris, and even animal carcasses (see Figure 28). Upon closer inspection, small living organisms (probably fly worms) were visible in the blackened, stagnant liquid, reflecting once again the poor sanitation. These observations reflect not only gross environmental contamination but also a breakdown of even the most basic pollution control mechanisms. Visual inspection suggested that the landfill's geomembrane liner was in visibly poor condition, with signs of wear and possible tears in the percolation and drainage systems. As a result, the leachate collection is most likely very inefficient, allowing contaminated liquid to infiltrate surrounding soil and potentially the groundwater table. This can be partially confirmed by the satellite views (see Figure 21), where we can clearly see the significant diminution in the leachate quantity collected, despite the increase in total amount of waste. The basin, originally intended to prevent groundwater contamination, now poses a serious environmental hazard in its own right.

Figure 28: Contaminated and polluted leachate basin

In light of these observations, it is clear that Essaouira's landfill no longer fulfills the basic criteria of a controlled landfill. The absence of operational control, insufficient staff, unmanaged leachate, lack of environmental safeguards, and widespread informal activity all point to a situation more akin to an open dump.

4.4.2 Recycling Pathways

In the absence of municipal waste sorting, recycling in Essaouira is driven by private initiatives and informal practices. Interviews with stakeholders consistently emphasized that neither group receives substantial support from local authorities, and their operations remain parallel to the official municipal waste management system.

One example of private sector involvement is TRIVALDEC, a company engaged in the collection of recyclables that are separated at the source by certain hotels, restaurants, and households. Their operations involve collecting, verifying, and sorting materials such as plastic, metal, glass, and cardboard. The materials are then compacted (see Figure 29) and sent to recycling facilities in Casablanca, as Essaouira lacks any local recycling infrastructure. They also collect large volumes of cardboard and plastic directly from distribution chains such as Carrefour and Aswak Assalam, where compacting machines have been installed. TRIVALDEC reports handling around 30 to 40 tons of recyclables per month, with volumes rising to about 50 tons during peak tourist seasons. Businesses pay for the collection service, but individuals can drop off recyclables free of charge. By bridging the gap between local waste producers and national recycling channels, TRIVALDEC provides a concrete example of how private initiatives can contribute to reducing landfill volumes and promoting circularity at the local level.

Figure 29: Compacted plastic waste (TRIVALDEC)

Another private initiative is MIKA, a company that coordinates and designs supply chains for plastic waste recycling. They organize beach clean-ups, paying individuals to collect waste, which is later passed on to partners who transform it into polyester fibers and textiles used in fashion items like handbags. Over two years, MIKA has collected approximately 100 tons of waste through beach clean-ups. In parallel, they also buy pre-sorted recyclables from individual collectors and facilitate their transfer to recycling facilities, totaling roughly 2,000 tons in the same period. Looking ahead, MIKA plans to build a recycling platform near the anticipated CEV (see Section 4.4.3), which would enable them to buy sorted waste from the facility and repurpose it into urban furniture or resell it to other recycling plants.

Alongside these private actors, a considerable share of recycling in Essaouira is performed by informal waste pickers. These individuals operate throughout the city, recovering recyclables from communal bins, wild dumps (see Figure 30), and areas such as the green belt (see Section 4.2). Formal collectors from official collection company such as ARMA also tend to retrieve some of the valuable waste they collect for themselves to sell it afterwards. Their focus is typically on high-value materials like plastics, metals, and cardboard, which are sold to intermediaries and ultimately processed in Casablanca. Informal waste pickers are also active at the landfill site (see Section 4.4.1), where they work despite official restrictions. Their contribution to the local recycling ecosystem is significant, yet their working and living conditions remain very poor.
Across Morocco, and despite their importance, informal waste pickers remain excluded from the formal municipal waste system, as explained in Section 2.2. Similarly, in Essaouira, there are currently no cooperative structures or official frameworks to support or integrate them. The potential CEV (covered in Section 4.4.3) includes a clause mandating the integration of informal waste pickers into its future operations. Project documentation outlines measures to support their inclusion, including access to formalized sorting platforms and protective equipment. This integration is not only a matter of social justice but also of economic viability. Indeed, if waste pickers continue to recover and sell recyclables independently, the volume of recoverable material available to the CEV may be reduced, threatening the ability of the project to meet financial and recovery performance targets.

Figure 30: Informal waste pickers searching for valuable materials

Overall, several structural limitations continue to hinder the development of an effective recycling ecosystem in Essaouira, and more broadly across Morocco. A major constraint is, once again, the absence of systematic waste separation at the source. Plastics, in particular, are typically collected mixed with organic waste and other contaminants. This significantly lowers the quality of the material and complicates its reuse in industrial recycling processes. Plastics recovered from landfill sites are especially degraded and dirty, requiring intensive cleaning and sorting before they can be recycled, if they are recyclable at all. This contamination reduces the market value of collected plastics and diminishes the economic incentive for actors involved in the recycling chain.

Further complicating the process is the current regulatory framework governing plastic reuse in Morocco. According to article 5 of "Law No. 28-00 on Waste Management and Disposal", 2006, recycled plastic is not authorized for use in food-contact packaging. This blanket restriction applies even to recycled PET, which is commonly reused for bottle-to-bottle recycling in many countries. The law is enforced by agencies such as the ONSSA (National Food Safety Office) and IMANOR (Moroccan Institute for Standardization), which regulate packaging safety standards (Martonakova, 2024). As a result, recycled plastics in Morocco cannot access one of the most promising and high-value reuse markets, the food and beverage packaging. This limitation thus drastically reduces demand and prices for recycled materials, which discourages investment in advanced recycling infrastructure. As an alternative or complementary approach, plastic credit schemes could offer a promising mechanism to continue incentivizing plastic collection and recycling despite low material value. By monetizing the environmental service of removing and recycling plastic waste rather than relying solely on the resale of materials, these credits could help fund recovery programs and integrate informal waste pickers. The potential of such mechanisms will be explored further in the diagnostic phase.

The potential for overall recycling can however be evaluated by computing the recyclable market value. This will be done through a simple calculus using Equation 1.

$$\text{RMV} = \sum_{i=1}^{n} (Q_i \times P_i) \tag{1}$$

where:

- Q_i: Quantity (in tons) of recyclable material i generated
- P_i: Average market price (in MAD) of recyclable material i
- n: Number of recyclable material types (e.g., plastic, cardboard, metal, glass)

In the case of Essaouira, with its average of 85 tons of waste generated per day, increasing to 110 tons during the summer months (June to August), the total amount of waste generated per year is around 33.325 tons. Based on number from Section 2.3.1 and the study from DGCL (2012), we can compute the share and quantities of each of the recyclable materials. Plastic therefore represents around 3000 tons per year, paper and cardboard account for approximately 1670 tons, glass for 670 tons, and metals only 330 tons.

Table 3 shows the average price of resale of the different materials. This was based on interviews with informal waste pickers, and stakeholders from the collecting and recycling industry in Essaouira.

The final RMV can thus be easily computed:

$$3000 \times 3500 + 1670 \times 700 + 670 \times 450 + 330 \times 2500 \approx 12,795,500\text{MAD} \quad (2)$$

This means that each year, up to 12,795,500 MAD (or 1,218,850 EUR) could be retrieved from collecting and selling recyclables in Essaouira. This is equal to around $0.383MAD/kg$.

Table 15: Average market prices of recyclable materials (in MAD per ton)

Material	**Price (MAD/ton)**
Plastic	≈ 3500
Paper & Cardboard	≈ 700
Glass	≈ 450
Metal	≈ 2500

It is also important to estimate the contribution of informal waste pickers to Essaouira's recycling stream in order to understanding the real extent of local recovery activities. However, no official data on informal recycling volumes is available, and a bottom-up estimation was thus conducted based on national figures, field interviews, and reasonable assumptions grounded in Essaouira's demographic and socio-economic context.

According to a study referenced by Rachid (2020), Morocco is home to an estimated 34,000 informal waste pickers. Given that most of these individuals operate in urban settings, this number can be related to Morocco's urban population, which stood at approximately 25.52 million in 2023 (Statista Research Department, 2023). This yields a ratio of approximately 0.133% of the urban population engaged in informal waste picking:

$$\frac{34,000}{25,520,000} \approx 0.00133$$

Applying this proportion to Essaouira's population of roughly 83,000 inhabitants gives an estimated 110 informal waste pickers active locally:

$$83,000 \times 0.00133 \approx 110$$

Based on interviews with several waste pickers, it was found that one individual can collect an estimated 15 kg of recyclable waste per day. This estimation is supported by reported average collection of approximately one standard plastic bag (1.5–2 kg) per hour over an 8–10 hour workday. Moroccan people usually work six days a week, which can be rounded to 300 working days per year (accounting for holidays). The annual collection per picker is then:

$$15 \text{ kg/day} \times 300 \text{ days} = 4.5 \text{ tons/year}$$

Thus, the total amount collected annually by informal pickers in Essaouira is around 500 tons.

To this, we add the 480 tons/year collected by TRIVALDEC (based on their declared monthly average of 40 tons), bringing the subtotal to 980 tons/year.

While MIKA collects significant amounts nationwide (2,000 tons over 2 years), their specific contribution in Essaouira is harder to isolate. However, we can reasonably estimate the presence of other smaller actors and recovery activities, such as additional restaurant and shop partnerships or NGO-led clean-ups, to add at least 200 tons/year, reaching a total of 1180 or approximately 1200 tons per year.

With a total annual waste generation of around 33,325 tons (computed earlier in this section), this leads to an estimated recycling rate of:

$$\frac{1,200}{33,325} \times 100 \approx 3.6\%$$

This number is slightly below the national average informal recycling contribution of 5%, as reported by WWF (2019). However, this is to be expected, given the absence of structured recovery facilities or sorting incentives in Essaouira. The estimate therefore aligns with national trends while reflecting the lower institutional support and infrastructure currently available in the city.

4.4.3 Future Development in Waste Treatment

Despite the critical challenges facing Essaouira's current waste disposal system, some promising initiatives are being planned to reverse the trend. The municipality is aware of the inadequacies of the current landfill and has begun developing proposals for improving and rehabilitating it.

One of the most ambitious projects under consideration is the establishment of a "Centre d'Enfouissement et de Valorisation" (CEV), or Burial and Recovery Center. This facility is designed to replace the current, malfunctioning landfill system with a more integrated and environmentally responsible solution. It will thus be built on the same site as the current landfill. The goal of the CEV is twofold: to bury non-recyclable waste in a controlled environment, and to recover valuable materials through sorting and composting operations. According to national guidelines set by PNDM, the center must achieve at least 10% waste recovery, a target Essaouira hopes to exceed, with bidders in the 2025 tender process having proposed rates of 11% to 12% recovery. The project specifications require the CEV to be equipped with a platform for sorting recyclables, a composting unit for organic matter, and properly lined burial cells for residual waste. These operations would be supported by a weighbridge, vehicle washing station, fencing, leachate and gas management infrastructure, and administrative buildings. The convention also requires the project to formally include current informal waste pickers at the site, as explained in Section 4.4.2.

The CEV is expected to operate as a provincial hub, serving not only Essaouira, but also 19 surrounding municipalities. These municipalities would contribute financially based on their tonnage delivered to the facility. To improve logistical coordination, two new waste transfer stations are planned in Tamanar and Hed Draa, at 70km and 30km respectively from Essaouira. The total projected investment is estimated at 66 million MAD, with the central government (Interior Ministry and Ministry of Environment) expected to finance two-thirds (44 million MAD) and the municipality the remaining third. The facility is projected to operate over a 20-year horizon. However, implementation has been delayed for over six years. Originally proposed before the COVID-19 pandemic, the project was first slowed by the health crisis and then rejected twice by the Ministries of Interior and Environment due to high estimated costs. A third revised proposal is currently under ministerial review, with a decision expected in the coming months.

Despite optimism from the municipality's side, doubts remain about the project's feasibility. Interviews with stakeholders revealed a lot of skepticism, a lot of them believing that the project will never take place, notably because of the lack of visible progress and the constant delay. Some also cite the stalled or underperforming CEVs in cities like Marrakech and Fès, attributing their difficulties to market challenges, such as low plastic resale prices, reportedly driven by lobbying pressures that reduce economic incentives for recycling. Composting poses similar problems, since the product must be certified to be commercialized legally, which increases costs and complicates distribution. Notably, no waste-to-energy solutions were proposed, highlighting a potential area for further investigation during the diagnostic phase, if the CEV project continues to be delayed or rejected.

It is also important to note that the plan for the CEV shown in Figure 31 appears increasingly outdated. Designed several years ago, it does not reflect the current reality on site. For example, satellite imagery (see Figure 21b) shows that several areas initially designated for infrastructure such as material storage, buildings, or platforms (highlighted in orange on the plan) are now occupied by uncontrolled waste sprawl. This raises concerns about whether the site layout is still viable and whether a revised technical assessment is needed before launching implementation.

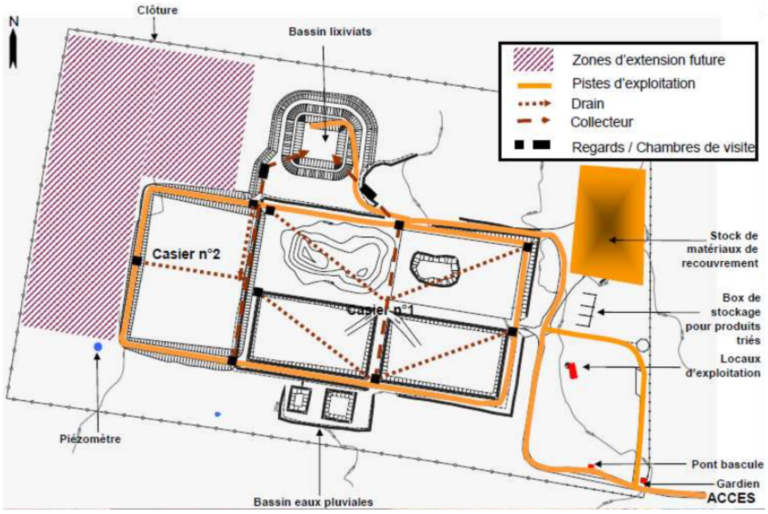


Figure 31: Landfill plan with CEV project implementation (dashed and orange zones)

Closely linked to the CEV is a public works project aimed at rehabilitating the current landfill. With an estimated budget of 20 million MAD, the plan includes re-compacting and properly redistributing existing waste, installing leachate and gas treatment systems, greening the surrounding area, and safely capping the landfill. Unlike the CEV, this project falls outside the delegated management framework and does not require ministry approval. However, it cannot be launched until the CEV is approved and operational, since there would otherwise be no alternative waste disposal site. Nonetheless, given the severe mismanagement currently observed at the landfill, the prospects of executing such a technically and environmentally demanding rehabilitation project should be approached with cautious skepticism.

In parallel, the TouMaLi initiative introduced in Section 2.3.3, led by the University of Rostock and supported by German funding, is piloting a small-scale tourism waste recovery center in Ghazoua. The goal is to characterize, collect, and sort tourism-related waste and divert it from landfills and the marine environment. This pilot project complements the CEV by tackling source-specific waste and raising awareness among hotels and the tourism sector. While its operational scale is limited, it aligns with broader efforts to reduce coastal pollution and promote circularity in Essaouira. Another limitation is that, similarly to the CEV, TouMaLi does not raise awareness of good waste management practice or engage the local community in separating its waste at the source.

Overall, together, these initiatives represent a long-overdue shift toward more sustainable waste management in Essaouira. But while the technical specifications have been drafted and submitted, the success of both the CEV and landfill rehabilitation ultimately depends on higher-level institutional approvals, stable financing, and consistent local commitment. Until then, Essaouira's waste treatment will remain in a state of limbo, with recovery ambitions on paper but no infrastructure yet in place.

4.5 Awareness and Public Engagement

Public awareness and citizen engagement are essential pillars of sustainable MSWM. However, the fieldwork conducted in Essaouira revealed that local cultural attitudes toward waste remain weak. Although less than 5% of respondents in the public survey admitted to littering, numerous open-ended responses pointed fingers at others, denouncing the widespread habit of throwing waste in the streets. These observations were confirmed on-site, where littering practices were visible in both central and peripheral areas. This disconnection between individual responsibility and collective behavior illustrates the low level of awareness and respect for waste-related norms. For instance, despite the legal ban on single-use plastic bags in Morocco, plastic bags are still systematically handed out by shopkeepers for even the smallest purchases, such as a single fruit or a pack of cigarettes.

Local authorities and stakeholders acknowledged these challenges. Interviews with municipal staff and partner organizations highlighted the difficulty of shifting mindsets. Although ARMA, the city's delegated waste management operator, is contractually obligated to allocate 1% of its budget to awareness-raising campaigns, survey results indicate a significant gap in impact, as around 70% of respondents reported never having received any form of instruction on waste management, while 50% expressed a desire to be educated on the topic.

Despite this, some awareness initiatives do exist. The largest of these is the annual summer campaign sponsored by the ANP, with a dedicated budget of one million MAD. This campaign combines awareness stands on Essaouira's beach promenade (see Figure 32) with infrastructure like separated waste bins, and organized beach cleaning efforts. The initiative aligns with the Blue Flag certification criteria and aims to install responsible waste behavior among tourists and locals.

Figure 32: Awareness stand in collaboration with the ANP, Essaouira Beach

Awareness is also present in schools to educate children. Indeed, some campaigns exist to raise awareness about waste management or recycling for example. Some activities are sometimes performed such as cleaning days or waste separation. Some school even claim they have separate bins which are used correctly by students. However, they also express a lack of resource to implement better waste management awareness. Teachers also explained that they felt very few students and families were made aware of the good practices concerning proper waste management, such as separating their waste, or not littering it.

Other awareness campaigns are conducted in schools, often in partnership with local NGOs. One active in this space is Surfrider, which runs the "Initiative Océane" program. The program combines educational discussions with hands-on waste collection actions on beaches, rivers, and public spaces. Waste is first collected, then sorted, quantified, and analyzed with participants (see Figure 33). Multiple interventions are carried out over time at the same location to retrieve the data and study the change. These campaigns are typically organized in schools, but they also sometimes target other specific groups, such as digital nomads (like the one in which I personally participated), to raise awareness across diverse segments of the population. According to the NGO, students are generally engaged and very enthusiastic. In addition to the "Initiative Océane", Surfrider also organizes large-scale cleanups approximately every two to three months, although the size of these clean-ups tends to decrease with time, due to the high demanding efforts of organizing them, and the limited availability of the six volunteers present in the region of Essaouira.

Unfortunately, the president of the NGO explained that the impact of these efforts is often limited to more environmentally conscious groups such as expats and students. According to her, engaging local businesses remains a challenge, with many continuing to dispose of waste improperly.

Figure 33: “Initiative Océane” sorting activity, Sidi Kaouki Beach

Overall, while isolated awareness campaigns are being implemented, their scale, frequency, and inclusivity remain limited. A stronger, more systematic approach to education and community mobilization, especially targeting youth, business owners, and households, is essential if sustainable behavior change is to be achieved. Without active public participation, even the most advanced technical waste solutions are likely to fall short.

4.6 Legal Framework Implementation

Despite Morocco's strong legal foundation for MSWM, as seen in Section 2.4, fieldwork revealed that the implementation of these laws in Essaouira remains limited.

National legislations such as "Law No. 28-00 on Waste Management and Disposal" (2006) and "Organic Law No. 113-14 on Local Governments and Communes" (2015) require municipalities to develop a formal waste management master plan with defined goals, timelines, and responsibilities. However, fieldwork revealed that the municipality of Essaouira does not currently have such a documented plan. Municipal officials acknowledged the absence of a formal strategy, even though there are intentions to improve waste treatment infrastructure in the coming years. The lack of a concrete, forward-looking waste management plan limits the city's ability to monitor progress and secure targeted funding or partnerships.

"Framework Law No. 99-12 on the National Charter for Environment and Sustainable Development" (2014), which promotes sustainability and calls for the integration of environmental concerns into public services, including support for recycling and waste reduction, also appears weakly enforced at the local level. Recycling in Essaouira is primarily driven by private actors and the informal sector, who operate with little to no institutional support. Although new projects to improve recycling have been discussed, their implementation remains uncertain.

"Law No. 77-15 Prohibiting the Manufacture, Import, Export, Marketing, and Use of Plastic Bags" (2015) is a clear example of the gap between legislation and enforcement in Essaouira. Although plastic bags initially disappeared from circulation following the law's introduction in 2016, field interviews confirmed that they have since made a strong comeback. Shopkeepers cited consumer preference for plastic bags due to their strength and lightness, and continue to distribute them openly. While Law 77-15 is technically in force, enforcement appears weak, particularly in informal markets. Plastic bags thus end up being littered and scattered all around with the wind (see Figure 26 of such example at the landfill). Local authorities in Essaouira acknowledged the widespread use of plastic bags but explained that they are not directly responsible for enforcing the ban. Indeed, implementation is managed by an inter-ministerial committee composed of the Ministry of Industry, Ministry of the Interior, Ministry of Justice, Ministry of Environment, and the Customs and Excise Administration. These entities are in charge of industrial compliance, border control, inspections, legal prosecution, and public awareness (Best Practices Waste MED, 2015). However, their limited visibility at the local level significantly undermines the effectiveness of the ban, especially in smaller coastal cities like Essaouira.

Finally, while coastal protection efforts under "Law No. 81-12 on the Protection and Development of the Coastline" (2015) are partially respected—particularly in the form of beach cleanups and restrictions on beachfront dumping—evidence of wild dumping near the shoreline highlights inconsistent enforcement (see Figure 14). These informal dumps not only violate national law but also undermine the city's environmental image and tourism appeal.

Overall, the gap between Morocco's legal commitments and their practical enforcement in Essaouira reflects common governance challenges in decentralized waste management systems. These include limited municipal capacity, weak inter-agency coordination, and the absence of formal planning tools. Strengthening local implementation mechanisms will be key to aligning Essaouira's waste management practices with national sustainability objectives.

4.7 KPI-Based Performance Assessment

This section builds upon the descriptive analysis presented in previous Sections 4.1 to 4.6 by applying the consolidated KPIs defined in Chapter 2.5, and more precisely in Table 3. The evaluation is conducted based on the analytical framework outlined in Section 3.2, which details the assessment criteria and scoring thresholds for each KPI. Using the data collected through fieldwork and literature review, each KPI is used to evaluate a specific dimension of Essaouira's MSWM system. This structured assessment enables a more objective understanding of the system's current strengths and weaknesses, and facilitates comparisons with international benchmarks. The results presented here serve as a foundation for identifying key inefficiencies and formulating targeted recommendations in the next chapter.

4.7.1 Collection Efficiency

The first sub-indicator here is the Collection Service Quality, which is measured according to Table 4. For the case of Essaouira, although officials report a collection coverage of 100%, a score of 1.5 is awarded because of the missing waste separation at the source. The collection points are however accessible and deserved frequently for most part of the population. It can be argued that the score could drop to 1 for some rural areas, where frequency or access to communal containers is less good.
Table 5 gives the threshold for the condition of bins and the citizen satisfaction concerning waste collection services. Both indicators received a score of 1. As mentioned is Section 4.2, 60% of people report damaged or overflowing bins and a majority is unsatisfied with collection services in general.

The weighted average of these scores results in a final score of **1.25**, corresponding to **poor performances** in collection efficiency.

4.7.2 Public Space Cleanliness

The indicators of Public Space Cleanliness were assessed according to Table 6.
The cleaning frequency and coverage are awarded with a 3, as cleaning occurs daily and over the entire territory. It could however be argued that this is only the case for some locations, as several remain underserved. However, no precise data was given and it is thus based on the statement of the municipality.
The public bin availability was awarded with a 1, considering the very low presence of public litering bins in the city. Citizen satisfaction also scored 1, as 70% of respondents to the survey expressed dissatisfaction with public cleaning services (see Section 4.3).

The final weighted average scored was **2**, or **mediocre performances** in terms of Public Space Cleanliness.

4.7.3 Waste Generation Rate

The waste generation rate scored a **1**, according to Table 7. Indeed, the waste generation of Essaouira was considered to be around 85 tons per day (see Section 4.1), which results in 1.024 kg/capita/day. This slightly exceeds the threshold of 1 kg/capita/day deemed mediocre. The performance is thus considered **poor**.

4.7.4 Waste Recovery

The assessment criteria for Waste Recover are expressed in table 8. The waste separation indicator and presence of MRF scored 1 because of the absence of such systems in Essaouira.
The recycling rate also scores 1, as the recycling rate was estimated at ≈3.6% in Section 4.4.2, well below the 5% threshold. The final average is thus **1**, or **poor performances** in waste recovery.

4.7.5 Waste Disposal

First, for the waste disposal, the landfill condition had to be assessed according to Table 9. Based on the observation from Section 4.4.1, only one criterion was met out of the 10 points checklist. This was the presence of bulldozers and heavy equipment on site, although it could be argued that there were not enough. The landfill is thus considered as an open dump, and scores a dramatic 1.
The other indicators are evaluated based on table 10. Since 100% (minus the 3.6% recycled) supposedly end up in the landfill, the percentage of waste landfilled scores 1. The presence of open dumps score a 1, as several were observed, as explained in Section 4.2. The leachate COD and BOD/COD ratios scored 2 and 1 respectively, according to the study of Chiguer et al. (2016) covered in Section 2.3.2, which results in 1.5 for leachate quality.

The final weighted average score was of **1.1**, corresponding to a **poor** waste disposal method.

4.7.6 Financial Sustainability

Financial Sustainability indicators were rated following Table 11. MSWM expenditure per year is 28 million MAD. With its nearly 83,000 inhabitants, the annual MSWM expenditure per capita is thus around $337MAD$, scoring a 2. The RMV was computed in Section 4.4.2 and is around 0.383 MAD/kg, which also scores a 2. It is worth noting that the score is closer to 1, because of its high organic content which has no value, and low value of plastics in general in Morocco. Overall, the final weighted average score was of **2**, corresponding to a **mediocre** financial sustainability.

4.7.7 Public Engagement

The Public Participation was rated according to Table 12 and a score of **2** was awarded, as some awareness campaign exist (see Section 4.5), although it could be argued that these campaign do not have a lot of impact on public participation. Nevertheless, the assessment considers it **mediocre**.

4.7.8 Informal Sector Role

The role of the informal sector was evaluated based on Table 13. The presence of informal waste pickers is scored 3, as they are the main source of recycling activities, as seen in Section 4.4.2. However, their integration was rated a 1, since no integration or support currently exist for these activities in Essaouira. The final score is thus **1.5**, or **mediocre**.

4.7.9 Institutional Framework

Finally, the institutional framework was scored according to Table 14. The existence of municipal waste plan received a score of 1 because of the absence of such plan. The plastic and litter regulation received a 2, because of the existence of regulation concerning littering and plastic use (e.g.Law 77-15 2015) but their weak or close to no enforcement (see Section 4.6).
The environmental oversight and citizen access was rated a 2, as a council supervising ARMA's performances exist (see Section 4.2), but citizen access is still weak.

The final score is thus **1.7**, or **mediocre** for the institutional framework.

4.7.10 Summary of Diagnostic Performance Assessment

Table 16 below summarizes the results of the KPI-based assessment presented in this chapter. For each KPI, the final score (on a scale from 1 to 3) is reported alongside its qualitative performance rating. The results clearly highlight the most critical weaknesses in Essaouira's current MSWM system, especially in areas such as waste recovery, disposal, and collection efficiency. These findings will inform the recommendations formulated in the strategic phase of the thesis.

Table 16: Summary of KPI Scores and Performance Ratings

Key Performance Indicator	**Score (1–3)**	**Performance Level**
Collection Efficiency	1.25	Poor
Public Space Cleanliness	2	Mediocre
Waste Generation Rate	1.0	Poor
Waste Recovery	1.0	Poor
Waste Disposal	1.1	Poor
Financial Sustainability	2	Mediocre
Public Engagement	2.0	Mediocre
Informal Sector Role	1.5	Mediocre
Institutional Framework	1.7	Mediocre

It is evident from the assessment that all KPIs fall into the "poor" or "mediocre" categories, reflecting systemic weaknesses across all dimensions of Essaouira's waste management system.

4.8 Diagnostic Summary

This section concludes the diagnostic phase of the study by summarizing key findings and answering the three research subquestions addressed in this part of the thesis:

1. **What are the key inefficiencies in Essaouira's current waste management system?**
2. **What is the impact of highly touristic seasons on MSWM?**
3. **What key performance indicators (KPIs) can be used to measure the success of the waste management practices?**

4.8.1 Key inefficiencies in Essaouira's current waste management system

The diagnostic revealed widespread shortcomings across nearly all components of the MSWM chain. First of all, waste is not separated at the source, which significantly undermines any potential for recovery or recycling. The high organic content present in the waste also complicates material recovery and disposal. Overall public satisfaction with waste collection is low, with bins often in poor condition and collection frequencies perceived as inadequate, particularly in peri-urban and rural areas. While public cleaning services are formally in place, their quality is uneven, and open dumps persist. Public litter bins are absent in many key locations and street cleaning workers report low morale. Moreover, the majority of residents also report being unsatisfied with cleaning services. There is no formal cooperation with neighboring municipalities for waste collection, despite evidence that they contribute to waste volumes in Essaouira's collection system.

Treatment and disposal present the most severe challenges. No formal recovery center exists, and recycling remains minimal (estimated at 3.6%), driven only by informal pickers and small private actors. The city's "controlled" landfill operates more like an open dump, where waste is not compacted or covered. The site lacks fencing, waste compaction and soil covering are not done, scavenging animals and informal pickers are present, and leachate quality is very poor and not managed at all. As for the informal sector, it is unrecognized and unsupported. Plastic waste is of low market value due to contamination and regulatory limitations on reuse. While a CEV is planned to improve treatment, the project has been delayed for over six years. Similarly, the planned rehabilitation of the current landfill appears difficult to execute under current conditions. However, hope remains on the TouMaLi project, which aims at taking care of the waste of the touristic sector.

On the legal framework side, legal enforcement is weak, and although national laws exist, such as the plastic bag ban, no actual fines are issued, and compliance is low. The municipality does not have any MSWM plan, nor does it track any waste indicators such as volumes, recycling rates, etc.
Finally, while awareness campaigns exist, cultural norms around waste remain weak, and most residents have never received any formal education on proper waste management.

4.8.2 Impact of highly touristic seasons on MSWM

Tourism significantly influences waste generation in Essaouira, with an estimated 30% increase in municipal solid waste during summer months. However, the impact on the waste management system, while present, appears to be relatively well managed, with field observations and stakeholder interviews revealing that collection frequencies and street cleaning efforts are reinforced during peak touristic periods. Additional staff and equipment are mobilized, particularly along the beachfront and public spaces, to maintain cleanliness and uphold Essaouira's image as a Blue Flag-certified coastal destination.

Awareness campaigns, such as those led by the ANP, are intensified in the summer season, promoting good practices among tourists and residents. Moreover, the burden of waste generated by hotels, restaurants, and other tourism-related businesses is largely absorbed by private collectors, such as TRIVALDEC, or through tripartite agreements with the municipality.

Also, the upcoming TouMaLi project, which targets the tourism sector with a dedicated waste recovery center, offers a promising step forward. It proposes a more structured approach to managing tourism-linked waste and integrating private and informal actors into the circular economy. While the peak season does place additional pressure on MSWM infrastructure, Essaouira's system has shown adaptive capacity to handle these fluctuations, although further integration, monitoring, and infrastructure will be necessary to sustain this resilience in the long term.

4.8.3 Key Performance Indicators (KPIs) for MSWM evaluation

To evaluate the performance of Essaouira's MSWM system, a set of consolidated Key Performance Indicators (KPIs) was developed based on the literature review and tailored to the local context (see Section 2.5). These indicators span technical, environmental, financial, social, and institutional dimensions, and are displayed in Table 2 and 3, while their assessment crietria were defined in Section 3.2. These KPIs were then used to conduct a structured performance assessment, which showed that all dimensions scored either "poor" or "mediocre" (see Section 4.7.10), and helped identifying key inefficiencies presented in sub-question 1.

5 Strategic Phase – Strategic Recommendations for Improving MSWM in Essaouira

Building on the diagnostic assessment presented in Chapter 4, this strategic phase aims to formulate a set of strategic, context-sensitive recommendations to improve the MSWM system in Essaouira. The diagnostic presented in Chapter 4 revealed systemic weaknesses across nearly all dimensions of the current waste management framework, including uneven waste collection coverage, the complete absence of source separation practices, the absence of waste recovery or treatment, unsafe and unmanaged landfill operations, limited public awareness, and weak enforcement of environmental regulations.
This chapter proposes a series of interventions to improve the performance of the MSWM system. The objective is to support a transition toward a more integrated, inclusive, and circular waste system tailored to Essaouira's coastal, touristic, and mid-sized urban context. Recommendations are structured around five priority areas: the first focuses on improving waste collection services and public cleanliness; the second addresses the introduction of source separation practices; the third examines the treatment of waste, both for centralized and decentralized solutions; the fourth concerns the rehabilitation of the current landfill; and the fifth considers the broader need for public engagement and improved enforcement of existing laws.

5.1 Waste Collection and Public Cleanliness

While Essaouira's waste collection and street cleaning services are largely operational, several deficiencies were identified during the diagnostic phase, especially in some peri-urban areas. These do not constitute the most critical failures of the system, such as the absence of source separation or the inadequate landfill infrastructure, but they nonetheless affect daily cleanliness, service equity, and public satisfaction. The following recommendations focus on pragmatic, low-cost measures to address these issues without requiring structural overhaul or significant investment.

5.1.1 Improving Bin Availability and Collection Frequency in Underserved Areas

While Essaouira's waste collection system is officially reported to cover the entirety of the urban area, Section 4.2 revealed a high dissatisfaction with both the availability of waste containers and the frequency of collection in several neighborhoods, particularly in peri-urban zones such as Ghazoua, Ouassane, and other remote areas where residents reported overflowing bins and damaged or missing containers.

Ideally, in order to fix this situation, the municipality should conduct a technical audit of bin distribution, capacity, and collection performance, using spatial data, waste generation estimates, and route optimization algorithms. However, such a study would require financial resources and institutional willingness that are currently lacking. The municipality maintains that current coverage is sufficient, and that no systematic review of service adequacy is planned. However, it was observed that it is currently not the case, and some actions therefore need to be taken.

First, the municipality, and ARMA especially, should prioritize the installation of additional bins in known underserved zones identified through the resident survey and field observations. At the same time, bins in poor condition should be systematically replaced (see Figure 13), as the current situation undermines both the functionality of the system and public trust in its fairness. As observed in multiple studies, consistent bin infrastructure is a baseline requirement for encouraging proper waste disposal and reducing littering behavior (Asare et al., 2021; Doris, 2019; Reingewertz and Ayalon, 2024).

In addition to local improvements, the municipality should also engage in dialogue with neighboring communes, notably Sidi Kaouki, whose residents frequently dispose of their waste in Essaouira's system. As highlighted in Section 4.2, this practice contributes to the overloading of collection points in Essaouira, without any formal coordination or cost-sharing mechanism. While this cross-communal dumping creates tensions, it also presents an opportunity, since Sidi Kaouki is a small locality, and it is unlikely to possess the financial or operational capacity to establish a standalone MSWM system. It would therefore be more efficient for Essaouira to formally extend its collection services to Sidi Kaouki, through a service agreement or inter-municipal cooperation mechanism. Such a collaboration would reduce illegal dumping and increase the cost-effectiveness of the overall system by pooling service demand and infrastructure. However, it should be accompanied by clearly defined service boundaries, financial arrangements, and public communication to avoid misunderstandings.

Also, in the absence of a full technical audit as mentioned above, the municipality should rely on a structured citizen complaint mechanism to guide future improvements in collection services. Currently, residents have no accessible or clear visible channel to report problems related to bin availability or collection. This limits the ability of ARMA or the municipality to react quickly or track recurring issues. Therefore, a dedicated complaint response platform, such as a centralized phone number, automatic WhatsApp line, or website, should be implemented. It should also be advertised on public bins, municipal signage, and social media. Then reports could be geolocated and tracked over time, allowing the municipality to identify patterns of dissatisfaction. Crucially, complaints should not be viewed as isolated grievances but as data points for service improvement. For instance, a high volume of complaints from a specific neighborhood about overflowing bins or delayed pickup should trigger a review of collection frequency or bin capacity in that zone. This complaint-based approach effectively replaces the need for a formal audit. If a community does not report issues, it may be reasonably assumed that the current service level is acceptable to them. Conversely, areas that repeatedly raise concerns should be prioritized for intervention. The system must however ensure quality control, and only actionable, location-specific complaints should influence planning decisions. Creating a transparent process for responding to and publishing resolution timelines would also improve credibility and encourage constructive participation.

5.1.2 Reinforcing Wild Dump Cleanup and Prevention

Wild dumps were identified in several parts of Essaouira's territory, particularly in areas with unclear administrative responsibility, such as the forested Green Belt (see Section 4.2). Also, no reliable system exists for citizens to report new dumps or track whether they have been addressed.

To improve the responsiveness, a two-part solution is proposed. First, a public reporting channel, similarly as proposed above, should be established to allow people to report illegal dumping. Second, ARMA or the municipality should maintain a public cleanup tracker, displaying before/after photos or lists of cleaned sites on the city website or a bulletin board at the municipal office. This could help enhance transparency and create a feedback loop where citizens can verify that their concerns are addressed.

These measures are not expensive, and they foster trust and visibility, which are often lacking in municipal services. In the long term, such systems can also provide informal data to guide preventive actions or inform regional enforcement strategies.

5.1.3 Enhancing Public Litter Infrastructure

There are very few public litter bins in Essaouira, and they are concentrated along the beach dike or roadways, while other high-traffic areas lack infrastructure. The beach itself is quite underserved, as there are no bins on the sand, despite large crowds throughout the year and recurring wind-blown litter, which contributes to marine pollution.

It is recommended that the municipality and the ANP upgrade seasonal beach bin systems, placing wind- and bird-resistant containers directly on the sand during peak months. Also, some litter bins should be installed permanently on the beach, as is currently done on the dike. In parallel, key pedestrian and commercial zones outside the beachfront should be targeted for bin installation as well. Placement should prioritize areas where informal dumping or litter accumulation was observed.

Nonetheless, improved infrastructure alone will not solve the issue of littering. It should be complemented by basic deterrence measures, such as posting signs in public spaces to remind people that littering is prohibited and subject to fines. These legal provisions should not remain purely symbolic: actual enforcement is necessary to ensure credibility. Occasional controls and the issuing of fines—especially in high-visibility areas such as beaches and the medina—would help discourage repeated infractions and reinforce the idea that littering is socially and legally unacceptable. These aspects are further developed in Section 5.5.

5.2 Waste Separation at the Source

The absence of source separation is a central weakness of Essaouira's current waste management system. All waste, regardless of origin or composition, is mixed at the point of disposal and transported directly to the landfill. This practice significantly limits the potential for material recovery, degrades the quality of recyclable fractions, and contributes to the rapid overfilling and environmental degradation of the landfill.

Introducing source separation is therefore a foundational step toward improving the performance and sustainability of Essaouira's MSWM system. As highlighted in the Section 2.6, all high-performing waste management systems in developed countries are built upon early-stage separation at the source. The separation of recyclables and organics before collection has proven to be the most effective way to enable material recovery, ensure high-quality recyclables, and reduce the environmental burden of landfilling. Without this step, downstream solutions such as recycling centers, composting plants, or even energy recovery systems remain largely ineffective or economically non-viable.

Moreover, the implementation of source separation aligns with Morocco's national waste management strategy and legal obligations under Law 28-00, which promotes the reduction of waste at source, recovery, and valorization as key principles of sustainable waste management."

5.2.1 Impact Analysis: Recovery Potential and Economic Value

In the case of Essaouira, the potential benefits of source separation could be substantial. With an average waste generation of around 85 tons per day, an organic fraction estimated around 60% and a recyclable share of 15-20%, even a basic two-stream separation (e.g., organic vs. rest, or recyclables vs. rest) could divert a significant portion of waste away from the landfill.
To better illustrate this potential, a quick estimation of benefits will be presented. This simplified calculation will provide an approximate idea of how much waste could realistically be separated, and what that could mean in terms of landfill cost avoidance and material recovery value over 20 years.
This is not intended to be a full economic feasibility study, since many precise figures are difficult to obtain or vary by context, but rather a back of the envelope calculation to support the case for early-stage implementation and further exploration.

If source separation is officially launched in Essaouira following the implementation of pilot projects, we could expect around 8-10% efficiency in the first two years, increasing to around 15% after five years. With continued investment and awareness, this could rise to 25–30% within ten years, and potentially reach 40-45% after two decades. These projections are illustrated in Figure 34 and are based on experiences from cities like Amman in Jordan, where pilot areas achieved 14% separation early on (Zayed, 2021), and Braga in Portugal, which targets 30% biowaste separation within three years of system rollout (Braga Verde, 2024). The numbers were adapted to the context of Essaouira, with lower cultural norms but high touristic pressure. For reference, Italy reached a national source separation rate of 61.1% in 2021, after more than two decades of gradual implementation and legal enforcement (European Environment Agency, 2022, IT report).

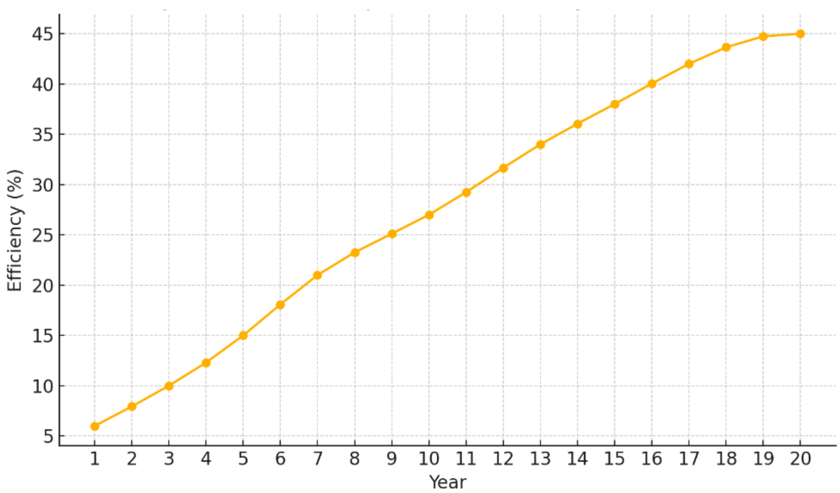


Figure 34: Estimations of waste source separation rates over the next 20 years

Each year, around 20 000 tons of organic waste and 5700 tons of recyclables are generated in Essaouira.
Assuming that waste composition remains similar throughout the years, we can make projections for the increase

of waste generation over the next 20 years based on Figure 8. Initial projections from the authorities estimated a 30% increase over 20 years, which actually happened over 10 years. With this information, we can compute the annual increase in waste generation. We assumed that waste generation follows an exponential growth, as Essaouira has experienced significant increases in recent years and is expected to continue growing due to rising population, expanding urbanization, and sustained touristic pressures:

$$1.30 = (1 + r)^{10} \Rightarrow r = (1.30)^{\frac{1}{10}} - 1 \approx 0.0266 \text{ or } 2.66\%$$

This annual growth can be applied to the share of organic waste and recyclables produced. Figure 35 thus projects the generation of organic waste and recyclables over the next 20 years.

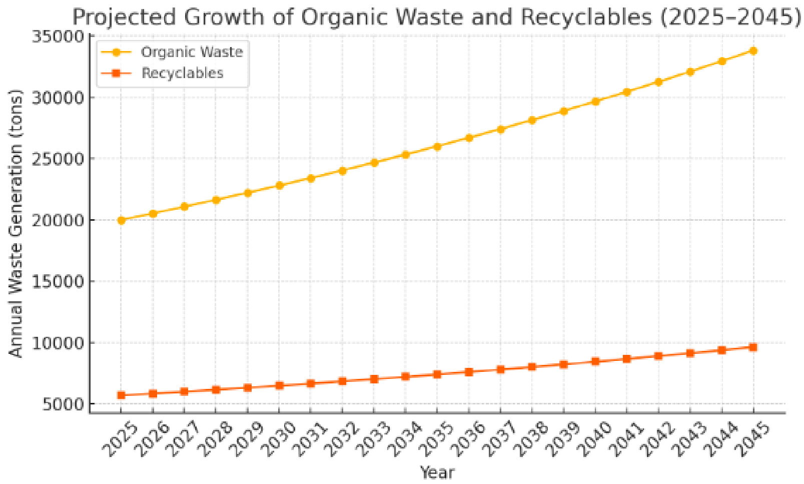


Figure 35: Projection of organic waste and recyclable generation over the next 20 years, assuming 2.66% annual growth

We can now try to estimate the actual benefits of introducing source separation. It is assumed that benefits will come from two main channels: the savings from reduced landfill burden and the revenues from material recovery.

Ouigmane et al. (2022) assume landfilling costs in Morocco to be around 25USD/ton, or 230MAD/Ton (June 2025 exchange rate).
Section 4.4.2 computed the annual RMV of Essaouira's recyclables to be around 12,795,000 MAD in 2025.
As for organic waste, a basic rule of thumb can be used to say that for each ton of organic waste undergoing biological treatment, around 400 kilos of compost are produced. According to local market prices, the price if compost is around 500 MAD/ton.

Now, to assess the long-term economic value of source separation in Essaouira, a Net Present Value (NPV) calculation is conducted over a 20-year horizon. The calculus considers the projected growth of organic and recyclable waste, the gradual improvement in source separation efficiency, and the expected revenues or savings from compost production, material recovery, and landfill cost avoidance.

While this section focuses on the potential benefits of introducing source separation, it is important to note that such a program would also entail significant implementation costs—including infrastructure, collection logistics, and public engagement. These cost considerations will be addressed in a later section outlining the implementation strategy.

For the current calculations, a discount rate of 5% was applied to reflect the time value of money, while material values were indexed with an annual inflation rate of 2%, based on expected future inflation rates (Statista, 2024). This includes the projected increase in landfill costs, compost prices, and the value of recyclable materials. The resulting NPV provides a realistic, inflation-adjusted estimate of the potential financial benefits of implementing and scaling up source separation in Essaouira. Its detail can be found in Table 17.
Overall, close to 103 million MAD could be generated over 20 years by implementing waste separation at the source in Essaouira. However, this estimation is based on several simplifying assumptions. For instance, it considers a basic composting scenario for organic waste and the external sale of recyclable materials without local value addition. In reality, the economic potential could be significantly higher if organic waste is treated through anaerobic digestion (producing both compost and biogas), if carbon credits are claimed, or if a local sorting and recycling facility is developed to retain more value in the region. Also, the efficiency of source separation could significantly vary based on its implementation method.

Table 17: Estimated annual benefits and NPV of source separation in Essaouira (2025–2044)

Year	Eff. (%)	Organic (t)	Recyc. (t)	Landfill Savings (MAD)	Recyc. Value (MAD)	Compost Value (MAD)	Total (MAD)	Discounted (MAD)
1	0.060	20000	5700	354660	767700	240000	1362360	1362360
2	0.079	20532	5851.62	488978	1031021	330894	1850893	1762755
3	0.100	21078.15	6007.27	648133	1331192	438594	2417919	2193123
4	0.123	21638.83	6167.07	834777	1670113	564897	3069787	2651798
5	0.150	22214.42	6331.11	1066002	2077458	721368	3864828	3179603
6	0.181	22805.33	6499.52	1346935	2556935	911477	4815347	3772951
7	0.210	23411.95	6672.41	1636398	3025942	1107358	5769697	4305437
8	0.233	24034.71	6849.89	1901196	3424502	1286548	6612246	4699199
9	0.251	24674.03	7032.10	2144599	3762837	1451259	7358696	4980655
10	0.270	25330.36	7219.15	2415670	4128627	1634695	8178991	5272251
11	0.292	26004.15	7411.18	2735635	4554334	1851216	9141185	5611895
12	0.317	26695.86	7608.32	3109825	5043145	2104433	10257402	5997291
13	0.340	27405.97	7810.70	3492666	5517232	2363503	11373401	6333135
14	0.361	28134.96	8018.46	3883173	5975163	2627761	12486097	6621644
15	0.380	28883.35	8231.76	4280205	6415438	2896434	13592077	6864922
16	0.400	29651.65	8450.72	4717832	6888154	3192578	14798563	7118362
17	0.420	30440.39	8675.51	5187202	7377213	3510203	16074618	7363968
18	0.436	31250.10	8906.28	5638606	7811415	3815670	17265691	7532964
19	0.447	32081.35	9143.19	6053329	8168662	4096314	18318305	7611634
20	0.450	32934.72	9386.39	6381175	8387955	4318170	19087299	7553493
Total NPV								**102,789,439 MAD**

5.2.2 Implementation Strategy: Pilots and Early Steps

This section outlines a step-by-step strategy for the successful rollout of source separation in Essaouira, aiming to progressively build technical, institutional, and public capacity over time. The approach is phased to align with local constraints.

Before implementing source separation citywide, it is essential to begin with targeted pilot projects. These pilots serve as experimental grounds to test logistics, raise awareness, and assess public willingness to participate. They also allow for the identification of barriers and the adaptation of strategies before broader implementation. Such projects are already taking place in bigger cities like Casablanca or Marrakech (Campitelli et al., 2023; Elbroumi et al., 2024).

In the case of Essaouira, two pilot projects are proposed as a starting point. Both would rely on the introduction of a simplified two-stream separation system for an easier adoption: one stream for the targeted fraction and one residual stream for the rest of the waste. One pilot project would focus on separating **recyclables** from the rest while the other would retrieve **organic waste**. The goal is thus to test the implementation of source separation on the two most valuable and abundant waste fractions.

Pilot Project 1: Recyclables

The first pilot project for the source separation of dry recyclables (plastics, paper/cardboard, glass, metal) is proposed to take place in the peri-urban neighborhood of Ghazoua. This area was identified as particularly suitable based on field survey results, which revealed a strong interest among residents in receiving guidance on waste separation and a high level of willingness to participate. Ghazoua offers a manageable starting point due to its moderate population size, relative spatial coherence, and proximity to existing collection routes, making it an ideal testing ground for a simplified recyclables-vs-rest separation system.

The project could start with a basis of 100 households, for an easier management and monitoring, and could last for around 6 months. The end goal would thus be to evaluate the participation, contamination rates, and collection logistics. After the first 6 months phase, the project could be extended to more households and a third separation stream for organic waste could be introduced.

Stakeholders Involved

The success of this pilot project will rely on the collaboration of several actors. First, the municipality of Essaouira should approve it, oversee coordination and provide some institutional support. ARMA, the waste collection company, should also be responsible for adapting its collection routes, and distributing bins or liners. However, it is important to consider the possibility that the company may not be willing to participate, a scenario which, unfortunately, might be very likely to happen. In that case, the distribution of bins could be arranged with the help of volunteers, such as locals or student from schools or the ESTE. These people, with the support of NGOs like Surfrider, could also be the ones mobilized to support awareness campaigns and community engagement. Additionally, local leaders in Ghazoua, such as professors from the ESTE and others, would play a key role in mobilizing households and relaying feedback.

As for the collection of the recyclables, since all of the waste collected by ARMA ends up in the landfill, private actors such as TRIVALDEC should be responsible for collecting them in order to recover their value. Moreover, interviews with the responsible of TRIVALDEC revealed that he was generally very enthusiast in participating in projects that raise awareness to the population and which improve the overall MSWM of Essaouira. He would thus also be the one ensuring downstream sorting and valorization of collected materials, since his sorting and compacting platform can handle the potential waste stream and is located nearby Ghazoua. Additionally, having separate pick-ups for recyclables versus rest generally reassures people in the fact that waste is actually recovered afterwards.

Finally, participating households would be expected to properly separate waste and engage actively in the evaluation process.

Needs Assessment and Preparation
Prior to the launch, a rapid needs assessment would help identify the most suitable collection model. This includes mapping participating households, evaluating where containers should be placed, and identifying potential constraints in collection logistics, such as space limitations. Other problems could consist of non-participating households disposing their mixed waste in the separated bins, or informal waste pickers coming and stealing the separated recyclables. Such obstacles should be taken into consideration.

Infrastructure and Logistics
Each household should receive a blue bin or liner for recyclables and a grey one for residual waste to store waste at home. They would then deposit the waste in designated communal containers placed strategically in their neighborhood. This approach minimizes disruption to daily routines and facilitates efficient collection by TRIVALDEC, who would retrieve the recyclable waste from these shared points once or twice per week, depending on the volume.

To reduce contamination, the communal containers for recyclables should be visually distinct and clearly labeled, and where feasible, placed in semi-supervised or low-traffic areas known to the participants. Efforts should be made to design the containers in a way that discourages non-participating households from using them, such as lockable lids or access-controlled bins when possible. This would also help counter informal waste pickers who might attempt to extract valuable recyclables. Moreover, for the latter problem, it is important to encourage participating households dispose of their recyclables as close as possible to the scheduled collection time in order to reduce the time during which valuable materials remain exposed in the communal bins. Clear communication of collection schedules will help reinforce this practice and preserve the quality and traceability of the collected recyclables.

All these measures aim to balance accessibility, operational efficiency, and the integrity of the sorted waste stream, while maintaining compatibility with the existing waste behavior in Ghazoua.

Awareness and Engagement
Of course, awareness campaigns should accompany the rollout to ensure residents understand the purpose and practical steps of the pilot. It should include door-to-door visits during the first month, printed flyers in Arabic with pictograms, and the creation of a WhatsApp or SMS communication group to maintain contact with participants. Influent people in Ghazoua should be contacted to support the project. A mid-term check-in event should be organized to reinforce messaging, collect feedback, and celebrate early adopters, fostering community ownership of the initiative. Ideally, awareness campaigns should continue throughout the entire pilot period.

Monitoring and Evaluation
Throughout the six-month pilot, data would be collected weekly to assess the volume and quality of the recyclables, participation rates, and contamination levels. Random bin inspections could also be used to evaluate sorting accuracy. At both the mid-point and the end of the pilot, short surveys should be conducted to gather household feedback and identify barriers to participation. These results should inform whether the pilot should be scaled up and if a third stream targeting organic waste could be introduced in a second phase.

Estimated Costs and Revenues
Based on household waste generation in Essaouira, the 100 participating households are expected to produce approximately 2 tons of dry recyclable waste per month (0.17kg per person per day), assuming an average of 4 people per household (Statista Research Department, 2025), which results in 12–13 tons of over the six-month pilot. Assuming an effective source separation rate of 40 to 60% —similar to other pilot projects (WWF-Kenya, 2024)—around **4.8 to 7.8 tons of recyclables** could be recovered over the pilot period. Depending on material type and purity, this could generate an estimated **11,500 to 18,000 MAD** in gross revenue in sales through TRIVALDEC.

On the cost side, the pilot would require funding for the distribution of color-coded bins or liners, the fuel for collection, and continuous community engagement. Rough estimates suggest the total cost could range between **10,000 and 20,000 MAD**, depending on the types of bins used and the scope of awareness activities (see

B.1). This includes printing materials, basic outreach, and bin procurement.

While the financial returns barely cover the pilot's expenses, the broader value lies in the operational lessons learned, the strengthening of partnerships, and the behavioral shift it may trigger among residents. Moreover, the pilot serves as a critical testbed for larger-scale interventions, and its results could support applications for further funding or integration into the formal waste management strategy. Moreover, if ARMA actually joins the project, some financing could be drawn from their "awareness budget".

Pilot Project 2: Organic Waste

The second pilot project proposed for implementing source separation concerns the organic waste, as this waste stream consists of more than 60% of the total waste generated in the region. It is therefore crucial to separate it during collection in order to recover its value. However, this project would not only consist of separating the waste, but also treating it. Indeed, since no recovery plant/center currently exists for treating organic waste in Essaouira, it is proposed to include a local composting project to the pilot.

For that reason, the proposed location should be a small neighborhood with sufficient space for composting activities and a strong sense of community ownership in order to ensure local engagement and facilitate operational logistics. The small village of Diabat is thus proposed to host this project. Located just outside the urban center of Essaouira, Diabat offers both proximity and favorable conditions for a small-scale composting initiative. The village has sufficient space, a manageable population size, and a strong sense of community, all of which support the practical and social dimensions of the project. In addition, the presence of a local school presents an opportunity to engage students and teachers in awareness efforts and potentially host the composting unit or use the resulting compost. While Diabat is not a definitive choice, it is recommended as a suitable location for this pilot based on preliminary observations. The final decision should follow further field validation and stakeholder consultation. The duration of the project could be around 6 months, allowing enough time to complete at least two composting cycles, monitor participation trends, and evaluate the system's technical and social feasibility.

Ultimately, the goal would thus be, similarly to the first pilot project, to evaluate the participation, contamination rates, and collection logistics, but also to test on-site biological treatment.

Stakeholders Involved

The success of this pilot project will require the collaboration of several local actors. Again, the Municipality of Essaouira should approve it, provide institutional backing and assist with site authorization and coordination. ARMA may be involved in the collection of residual waste, or in the management of the compost. If they agree to participate in the project, ARMA's staff could be charged with ensuring proper operation of the composting unit. Otherwise, local residents or school teachers and students could take responsibility for this task. However, it is strongly recommended to designate at least one trained person as the official operator of the composting system to ensure proper management of the compost. Voluntary support by students or residents can still be encouraged, but should complement this formal responsibility.

The local school in Diabat could serve as host for the composting unit and a partner in awareness-raising, with students and staff playing an active role in monitoring and education. Other volunteers could assist in community mobilization or training. Finally, households in the selected cluster will be expected to sort their organic waste properly and deposit it in the designated collection system for composting.

Needs Assessment and Preparation

Before launching the pilot, a preliminary needs assessment should be conducted to ensure the feasibility of composting in Diabat. This includes identifying a group of households willing to participate, and evaluating the volume and type of organic waste typically produced. The assessment should also determine the most suitable location for the composting unit, ideally within or near the local school, or in another secure and accessible public space. The exact site selection should consider factors such as space availability, shading, wind exposure, accessibility, and the potential for odor or pest issues.

The assessment should also identify a person or small team who will be trained and tasked with monitoring the compost process, including regular turning, checking temperature and moisture, and managing the carbon-nitrogen balance. This training should include practical sessions. Finally, key local actors who could support awareness-raising and community buy-in should be identified as well.

Infrastructure and Logistics

Each participating household would be provided with a small bin or bucket to store organic waste at home. Households would be asked to bring their waste to the communal containers, placed near the composting. These containers should be clearly marked, covered, and cleaned regularly to minimize odor and pest risks. Also food waste should not include meat, fish, dairy, or oily residues to limit health and sanitation risks, as these products are generally harder to decompose and require specific monitoring of the compost.

The composting system itself could consist of either static composting boxes or manually managed windrows, depending on the available space and budget. In both cases, multiple units should be set up to allow for a rotation system, where one pile is being filled, another is composting, and a third is maturing or ready for use. The composting site should be enclosed to prevent animal access, with signage explaining the process to increase visibility and educational value. Organic waste should be layered with dry material to ensure proper aeration and avoid unpleasant odors.

Also, given the strong wind conditions common in the Essaouira region, special attention should be given to protecting the compost pile from excessive exposure. If windrow is used, it should be placed in a sheltered area, such as behind a building or fence, and covered with a breathable tarp or compost fleece to minimize moisture loss and prevent the scattering of light materials.

Basic tools such as a pitchfork, watering can, and thermometer should be made available to support the composting process. The composting unit would be turned weekly and monitored by the trained responsible person(s). The process is expected to take 2–4 months before the first batch of compost is ready for use, either in school gardens, nearby farms, public green areas, or potentially sold to the golf property 1 km away.

It is also important to consider the fact that most household organic waste consists of food scraps, which are nitrogen-rich or "green" materials. However, in order for a compost to be of good quality, a Carbon-to-Nitrogen ratio (C/N) of 20:1 to 40:1 should be maintained. This means that the pilot will require an additional supply of carbon-rich or "browns" such as dry leaves or shredded cardboard to avoid odors or compaction. In terms of weight or volume,this is equivalent to around 2-3 buckets of "browns" for one bucket of "greens". A solution to obtain these brown materials would be to partner with local institutions such as the nearby golf course, which regularly produces leaf litter and dry clippings. This would help ensure a balanced composting process and reduce reliance on household-provided dry materials.

Awareness and Engagement
Obviously, for such project, community awareness and engagement are crucial in order to properly from the participants and evaluate their willingness to participate. Before launching the project, awareness campaigns should be conducted to inform residents about the purpose of the initiative, how to participate correctly, and the environmental and social benefits of composting. These efforts may include informational meetings with households, door-to-door visits, the distribution of illustrated flyers, and short presentations at the local school. During the implementation phase, continuous engagement will be necessary to reinforce good practices and minimize contamination. Clear, simple instructions should be visibly posted near composting sites and household collection points. Regular reminders—such as door-to-door check-ins or SMS messages—can help maintain motivation and correct any sorting mistakes early.

External stakeholders could also be brought to the site as well to raise awareness through hands-on workshops or demonstrations. For example, this could consist of visits/field trips from other schools of Essaouira. This would both raise broader awareness and foster the project's visibility as a replicable model for other communities.

Monitoring and Evaluation
To assess the success of the pilot, simple and practical monitoring should be carried out throughout the project. A local responsible person, supported by the school or municipality, can track basic indicators such as participation (how many households are contributing), contamination (presence of plastics or other non-compostable items), and the general condition of the compost (odor, moisture, temperature). These observations can be recorded weekly using a simple notebook or chart.

At the end of each composting cycle (every 2–3 months), a short evaluation should be done. This could involve informal conversations or short surveys with participating households to gather feedback on their experience, difficulties faced, and suggestions for improvement. The amount of compost produced and how it was used should also be noted. Finally, the person in charge could prepare a short summary of key outcomes and challenges, to help decide whether the project should continue, be adjusted, or be replicated in other neighborhoods.

Estimated Costs and Revenues
A rough cost and impact estimation was carried out to provide a general idea of the scale and feasibility of the composting pilot project. Two scenarios were considered: one involving 50 households and another with 100 households, each composed of four individuals, similarly as the first pilot project. Based on previous results, it is assumed that each person produces around 0.6 kg of food waste per day. To ensure proper composting and an good C/N ratio, approximately 1.4 kg of carbon-rich material per person per day is needed. This results in

a total estimated input of about 2 kg of organic material per person per day.

Again, similarly as pilot project 1, the participation rates were assumed to range between 40% and 60%. Based on this, the total amount of organic waste processed over six months was calculated, along with the expected compost output using a conservative yield of 400 kg of compost per ton of total input. While compost is valued at around 500 MAD per ton, it should be noted that demand in the region may be limited, as many local farmers still prefer manure due to the lower price. However, part of the compost could be distributed to the municipality or golf course for maintenance of green areas.

Estimated costs include the purchase of bins and containers, construction of composting boxes, basic tools and signage, awareness campaigns, training workshops, and site preparation (see B.2. Operational labor costs were not included, assuming that responsibilities could be managed by local volunteers, teachers, or municipal staff for the pilot phase.

Overall, the total estimated cost is approximately **16,900 MAD** for 50 households and **22,300 MAD** for 100 households. These are preliminary figures that should be refined during the implementation planning phase. In terms of revenues, if all the compost produced were to be sold at market value, the income could range between approximately **5,700 and 8,600 MAD** in the 50-household scenario, and between **11,500 and 17,200 MAD** in the 100-household scenario, depending on actual participation rates. However, these are optimistic estimates: in practice, a portion of the compost may be given away or used for non-commercial purposes. The revenue should therefore be seen as a maximum potential, rather than a guaranteed return. A full breakdown of assumptions, quantities, and outputs is provided in Annex B.2.

Although revenues are not expected to cover the initial costs, the primary objective of the pilot is to raise awareness, build community engagement, and test operational feasibility. If successful, future upscaling could allow for cost optimizations and improved economic viability.

5.2.3 Scaling Pathway: Medium- and Long-Term Strategy

Of course, the implementation of the two pilots projects is only the beginning. A phased citywide expansion of source separation is crucial to introduce waste sorting into Essaouira's regular waste management system. This expansion must be carefully planned and institutionalized to ensure sustainability. It will also require broader stakeholder involvement, including the municipality, the contracted waste service operator, local communities, and other partners.
This section will not provide a detailed analysis of each step that should be taken, but rather focus on scaling up in stages, integrating key drivers of successful source separation identified in the literature, and institutionalizing the practice through policy and partnerships.
Some mechanisms are also proposed to prevent regression after the pilot phase and to integrate source separation into long-term governance.

Expansion and Stakeholder Engagement

In order to expand the practice of source separation from pilot zones to the full municipality, Essaouira could adopt a phased expansion strategy. First, the city should build on pilot success by rolling out separation to additional neighborhoods similar to the pilot areas, refining what did not work, and expanding the scope. For the organic waste, however, it should be noted that local composting projects could not be implemented everywhere in the city, as space and lcoal involvement would certainly be lacking. Therefore, biological treatment plants should be installed to handle the separated organic waste as soon as wider source separation is introduced. This could consist of the coming CEV, if it were to actually be build. Then, the coverage of source separation should be increased gradually, dividing the city into phases or sectors, introducing source separation sequentially (e.g. a few districts), which would permit learning and adjustment before the next phase. Afterwards, Essaouira would move towards the full integration within a defined mid-term horizon (e.g. 3–5 years). This step would be achieving separation at source across all urban districts, and in the long term extending to suburban and rural areas of the province.

This phased approach allows for better implementation and adaptation based on feedback and results from small scale projects before scaling up, similarly as what is being done in Casablanca (Elbroumi et al., 2024).

However, such scaling cannot happen without active participation and collaboration of all stakeholders. The municipality retains full responsibility for household waste management under Moroccan law, so local authorities must lead the program, convene stakeholders, and set regulations. At the same time, the city's private waste collection operator is a critical partner for operationalization. Indeed, when scaling out of pilot projects, ARMA's participation becomes crucial, and the company should adapt its practices, such as planning new collection routes, adapting equipment (e.g. dedicate trucks or compartments for different streams), and train its staff for multi-stream collection. Their contract with the municipality should thus be changed as well to reflect these new responsibilities. Citizens and civil society are equally important actors. Local community associations, NGOs, and neighborhood leaders can help mobilize residents and maintain participation. In fact, local authorities must convince both citizens and sector stakeholders of the value of new waste practices so that sorting becomes a collective habit. Therefore, ARMA should be required to increase the share of its budget allocated to awareness. Moreover, funding and performance incentives such as bonus payments for achieving certain recycling rates, or penalties if separated waste is not properly collected, could be introduced between the municipality and ARMA to align the operator's incentives with the program's success. Overall, municipal officials and ARMA's managers should also collaborate, exchange regularly, and encourage feedback from citizens. Finally, ARMA should also be required to train its staff for separate collection of waste. This would include operational guidelines, technical training on handling different waste streams, and awareness sessions on the importance of source separation to ensure that collection staff are fully aware, enthusiast, and equipped to support the system's objectives.

Key Drivers for Long-Term Source Separation Success

Scaling up will succeed only if some key drivers of participation and sustainability are built into the program design. Evidence from scientific studies highlights several critical factors that influence long-term household waste separation behavior.

Clear policy and enforcement is the first important thing to put in place to ensure proper source separation. Households need to know that sorting is expected (and required) as an official policy. Introducing local decrees or bylaws after the pilot phase, for example, mandating separation of recyclables and organics, can institutionalize the practice. Enforcement should be phased and not take place directly. Initial voluntary compliance should first be reinforced by education, followed by gradual introduction of penalties for non-compliance once the system is fully in place. Hao et al. (2020) showed that, in a Chinese college, participation in waste separating rose from 10.1% to 17.8% after a citywide mandate, while the results from Chen et al. (2018) showed an increase of close to 50% in sorting rates after the introduction of a law on source separation. Chen et al. (2018) added that each 1% increase in households visited by inspectors added another 3.6 points to compliance. These studies were performed in China, where different socio-cultural norms exist, but they still provide good insights on the impact of introducing policies for waste source separation.

In Morocco's context, Law 28-00 already provides a basis for waste management by emphasizing the "polluter pays" principle, and it aims to strengthen provisions for segregated collection. The municipality of Essaouira could thus build on this by enacting specific regulations (e.g. an "arrêté" requiring source separation in Essaouira) to give the program legal teeth. This legal backing would ensure that source separation is not just a temporary project but a recognized municipal obligation.

Of course, legal enforcement alone is not sufficient to implement waste separation efficiently, and it should be backed by other mechanisms such as **financial incentives and funding**. In reality, introducing economic incentives can significantly motivate households to sort waste. Research show that even modest monetary rewards greatly increase willingness to separate recyclables. For example, Reingewertz and Ayalon (2024) explain that a 14$ monthly incentive more than doubled the chances of households sorting their waste. Other studies also emphasize the effect of direct payments on source separation, explaining that it is one of the most effective motivators (Alhassan et al., 2020; Asare et al., 2021; Yi et al., 2021). A waiver on disposal fee is also considered as an effective motivator, although this does not apply to the case of Essaouira because the service is currently free of charge for citizens.

Doris (2019) analyzes several studies and presents incentives different from direct cash payments. He proposes PAYT, DSR schemes, or vouchers. The latter consists of receiving credit points for good sorting practices, which can the be exchanged in local businesses, markets, etc. These can also be organized by neighbourhoods or buildings, pushing towards a sense of community and small competition in waste separation. The best buildings receive more points and a ranking can be displayed every month.

In the context of Essaouira, several considerations must be weighed when choosing appropriate incentive mechanisms. Although DRS could be an attractive option, particularly to encourage the return and collection of plastic bottles, its implementation in Morocco faces a key regulatory obstacle: recycled plastic currently cannot be used for food packaging, as seen in Section 4.4.2. Therefore, while DRS could be piloted in specific contexts (e.g., for glass or cans), its large-scale adoption may remain premature. Similarly, PAYT schemes for mixed waste are unlikely to succeed in the short term. As highlighted in Section 4.2, illegal dumping remains widespread even without a waste fee. Introducing such a system may only worsen the situation by incentivizing further uncontrolled disposal to avoid paying fees.

Instead, more feasible options include community-based voucher systems or reward schemes, where households or neighborhoods receive non-monetary benefits (e.g., market discounts, school supplies, event tickets) for good sorting practices. These can foster positive reinforcement, create friendly competition, and enhance local engagement without the backlash associated with punitive measures. Additionally, other low-cost, non-financial strategies, such as public recognition (e.g., certificates or signage for top-performing neighborhoods), or school-based contests, could reinforce participation and gradually build a waste-sorting culture.

These incentives generally work best when accompanied by other systems, as financial carrots alone cannot overcome the logistical and psychological barriers to separation. And if no financial incentive can be provided, it is essential to ensure that households do not bear extra costs for participating (e.g. providing free bins, free pickup of sorted fractions). Easy access to separated bins and clearly labeled, well designed bins are crucial to make separation as effortless as possible, as well as the free provision of bins for households(Asare et al., 2021; Doris, 2019; Reingewertz and Ayalon, 2024).

In Essaouira, the municipality should prioritize the free provision and strategic placement of standardized, color-coded bins, and ensure clear bilingual (Arabic/French) labeling to minimize sorting errors. Separated bins should also be distributed at no cost to households, with additional communal drop-off points in high-density neighborhoods. Collection schedules for each fraction must be integrated into the existing system described in Section 5.1, with dedicated routes and frequent pickups (e.g., daily for organics, bi-weekly for recyclables) to prevent overflow and discourage illegal dumping. To support this, a simple user guide can be used to reinforce correct sorting behaviors, and tracking bin usage could allow for adaptive adjustments.

Citizen education is the glue that holds a source separation program together over time. Ali and Marjaneh Kharrat (2022) showed that face-to-face sessions plus simple brochures on the economic, social, cultural and environmental benefits of sorting significantly boosts households' source-separation.

To ensure lasting impact, Essaouira should establish a continuous education framework. The municipality should launch a sustained outreach campaign—school programs, neighborhood workshops, and door-to-door demonstrations—explaining both the "how" (what to separate, into which bins) and the "why" (environmental benefits, potential revenue). Materials must be locally adapted, visually clear, and periodically refreshed to prevent message fatigue. Education efforts should also highlight the progress and positive impact of the program (for example, announce how many tons of compost were produced or recyclables sold) to keep citizens engaged and proud of their contribution. This outreach could include integrating waste-sorting modules into school curricula, partnering with local radio and social medias. Ultimately, the goal is to normalize waste sorting as a daily habit, which requires ingraining the practice through repeated messaging and visible leadership support. Municipal authorities and local leaders should lead by example to signal long-term commitment.

Preventing Regression and Ensuring Sustainability

After the excitement of pilot projects, there is a known risk that progress can regress. Residents might slip back into old habits, and authorities might lose focus To guard against this, the scaled-up program must include mechanisms for continuous reinforcement and improvement. The city should implement a monitoring system to track key indicators such as participation rates, quantity and quality of recyclables/organics collected, and reduction in residual waste. This could involve periodic audits or surveys (for example, ARMA staff checking random bins for proper sorting, or measuring contamination levels at sorting facilities). Public engagement should also be continuous, beyond initial education. As explained, awareness campaigns cannot be one-off. The municipality should thus set up programs or community-based initiatives that aims at improving waste separation in households.
Adaptive management is also key to avoiding regression. The program design should remain flexible to adjust based on feedback and changing conditions. For example, if certain waste categories prove too difficult for households to sort (due to confusion or inconvenience), the city could simplify the scheme (e.g. move from three streams to two streams temporarily) rather than see people give up entirely. Conversely, if participation is very high and contamination low in some areas, the city might pilot even more detailed sorting in those areas. The ability to pilot new solutions within the larger program keeps it dynamic and responsive.

Preventing regression also means planning for the long-term end-use of the collected materials. A common failure mode for source separation programs is when separated waste ends up not being recycled or composted, leading the public to become cynical. Essaouira must avoid this by ensuring that parallel investments are made in waste treatment infrastructure: the organics collected need to be composted or valorized, and recyclables need to reach recycling processors or aggregators. Treatment methods will be covered more details in Section 5.3.

5.2.4 Conclusion

Ultimately, source separation should not be seen as a standalone intervention, but rather as one essential component within a broader, integrated MSWM system. Its success depends on strong coordination with other elements such as efficient collection logistics, adequate treatment infrastructure, sustained public engagement, clear legal frameworks, and institutional support. The recommendations outlined above are therefore intended to serve as a foundational pillar in Essaouira's transition toward a more sustainable, inclusive, and circular waste management model.

5.3 Waste Treatment and Recovery Strategies

While improving collection services and introducing source separation are essential steps for a better MSWM, they must be supported by appropriate treatment and recovery strategies to reduce landfill dependency and environmental impacts. In Essaouira, no formal waste treatment infrastructure currently exists. All waste, regardless of composition, is disposed of directly at the landfill without any prior processing. This results in the rapid exhaustion of landfill capacity, uncontrolled greenhouse gas emissions, and the loss of recoverable materials.

Therefore, this section examines potential treatment strategies for Essaouira, building on the upstream improvements discussed in the previous sections. It begins with low-tech solutions that could be implemented in the short to medium term, such as the creation and implementation of small-scale composting/recycling units. It then evaluates more advanced centralized treatment solutions, including MRF, anaerobic digestion (AD) and other composting techniques, and incineration. These are not formal recommendations, but rather strategic options whose suitability depends on evolving technical, institutional, and financial conditions.

5.3.1 Decentralized and Low-Tech Solutions

Small-Scale Composting Units

Several of the treatment solutions presented in this section build on the upstream improvements proposed earlier, including the pilot project for source separation and composting in Diabat (see Section 5.2.2). As demonstrated in that case, small-scale composting units can offer a low-cost, low-tech, and community-based solution for treating organic waste locally. Provided that space, engagement, and basic training are available, similar initiatives could be replicated in other neighborhoods of Essaouira. Villages or peri-urban areas with schools, active community groups, or open land are particularly promising. While these projects may not significantly reduce total landfill volumes on their own, they serve a critical role in demonstrating decentralized solutions, building public awareness, and relieving pressure on central waste infrastructure.

Community-Based Recycling Initiatives

Community-based recycling initiatives consist of local engagement and low-tech solutions to improve waste treatment. This type of strategy is highly relevant for Essaouira, where formal recycling systems are lacking. As seen in Section 4.4, Essaouira currently has no formal system for recycling or sorting plastics, and has an small estimated recycling rate of around 3.6%. In response to these gaps, two complementary approaches can be recommended: plastic credit programs that financially incentivize waste collection, and decentralized small-scale recycling units that empower communities to transform plastic waste into valuable products. These initiatives, implemented together, could form a connected system to improve plastic recycling in Essaouira.

Plastic Credit Programs as Incentives

Plastic credits are an emerging market-based mechanism to encourage plastic waste cleanup and recycling. The concept is very similar to carbon credits: 1 plastic credit represents 1 kg (or 1 ton) of plastic collected or recycled (Empower.eco, 2025). Organizations like businesses or NGOs can purchase credits to offset their plastic footprint, thereby funding the removal of an equivalent amount of plastic waste from the environment. This practice is becoming more and more adopted, and its goal is to empower local waste pickers and communities through financial incentives, effectively turning littered plastic into an economic resource.

As noted in Section 4.4.2, plastic waste has particularly low value in Essaouira due to its contamination and the interdiction to reuse it for foodpackaging. Therefore, introducing plastic credits could be a solution to incentivize plastic separation, collection and recycling. The price of one credit depends on the type of project, but they are generally comprised between 140 and 670 USD (for 1 ton of plastic), according to World Bank (2024b). This variability reflects factors such as the type of plastic targeted, the project's location, the waste management method used (e.g., recycling, landfill diversion, ocean cleanup), and the extent of social impact, particularly in projects involving marginalized communities or developing regions. Due to its coastal location and developing country status, it is very likely that Essaouira could benefit from relatively high plastic credit prices. At this stage, it is however complicated to estimate the exact price and total potential revenues that could be generated with the introduction of credit plastic schemes.

However, access to plastic credit markets remains limited, particularly for small-scale or informal actors. Obtaining certification requires strict traceability, monitoring systems, and third-party verification, which can be financially and administratively out of reach for decentralized, low-tech initiatives. To overcome this barrier, it would be more feasible to establish a centralized coordinating body, such as a local cooperative, municipality-backed program, or NGO platform, that aggregates the efforts of smaller recycling units and manages the certification process collectively. Such an umbrella organization could facilitate access to the plastic credit market while ensuring transparency and economies of scale, thus enabling small local initiatives to benefit from this global mechanism.

Decentralized Plastic Recycling

To begin addressing the growing challenge of plastic waste while promoting local economic development, it is porposed that Essaouira implements a decentralized plastic recycling strategy based on small-scale, low-tech processing units. "Micro-factories" would enable local communities to transform plastic waste into useful products, reduce environmental leakage, and create jobs. Two initiatives exemplify this approach: **Precious Plastic** and **Plastic Odyssey**, both of which offer open-source, adaptable technologies for low-cost recycling operations in developing contexts. However, such initiatives are best suited for **private or community-based actors**, as the municipality of Essaouira is unlikely to directly invest in or operate small-scale recycling workshops. Instead, these micro-factories could be established by local entrepreneurs, cooperatives, or NGOs under municipal authorization or partnership frameworks. This approach would stimulate private-sector participation in waste valorization, diversify local income sources, and complement the municipality's broader waste management responsibilities focused on collection and disposal.

Both Plastic Odyssey and Precious Plastic promote decentralized, low-tech recycling solutions that can process between 200–600 t of plastic per year using modular machines such as shredders, extruders, and presses. Their open-source designs allow for locally built setups costing as little as 12,000–16,000 EUR, while containerized or semi-industrial micro-factories can reach investments of 50,000–100,000 EUR depending on scale and automation level (Plastic Odyssey, 2024; Precious Plastic, 2025). These systems rely on simplicity, adaptability, and local engagement, making them particularly suitable for medium-sized cities such as Essaouira. Below is a more detailed conceptual design of a pavers/tiles micro-factory tailored to Essaouira's context, outlining its key process steps, equipment, and expected performance, based on the open-source of Plastic Odyssey (Odyssey, 2023; Plastic Odyssey, 2024).

Process and equipment.

A typical pavers production line comprises a shredder (100–150 kg/h), densifier (50–100 kg/h), plastic–sand mixer (125 L), extruder (150–250 kg/h), hydraulic press with molds, and a cooling system. Auxiliary systems include ventilation, electrical wiring, sorting tables, and material handling equipment, with a total installed power of approximately 40–60 kW.

Throughput and yield.

The process blends approximately 40% plastic with 60% sand by mass. For a standard 20 × 16 cm road paver (6 cm thick), one square meter requires about 93 kg of mixture, equivalent to 37 kg of plastic. This means that 1 tonne of plastic can yield approximately 27 m^2 of finished pavers. At an operational rate of 200 kg/h, a workshop operating 8 hours per day and 300 days per year could process roughly 200–300 t of plastic annually, depending on feedstock availability.

Capital and operational cost.

The combined machinery investment is estimated at 58,000–76,000 EUR. Including installation, utilities, and basic infrastructure, the total CAPEX ranges from 65,000 to 90,000 EUR. In terms of OPEX, the main expenses include electricity, labor, maintenance, and consumables. The Plastic Odyssey guide (Odyssey, 2023) estimates an energy demand of about 275 kWh per tonne of processed plastic, or 27.5 EUR/t at a local electricity tariff of 0.10 EUR/kWh. Maintenance of shredder blades, extruder screws, and molds adds recurring costs, as do wages for 2–3 operators. Overall, annual operating costs are expected to range between 10,000 and 20,000 EUR, in accordance with a classical rule of thumb of 10–20% of CAPEX.

Revenues and payback. Assuming a conservative sale price of 8–12 EUR/m^2 and a yield of 27 m^2/t, a 200 t/year plant could produce 5,400 m^2 of pavers and generate 43,000–65,000 EUR in annual revenue. With CAPEX around 70,000–90,000 EUR and OPEX of 10,000–20,000 EUR, the payback period would range from 1.2 to 2 years, depending on market conditions, product quality, and plant utilization.

Risks and sensitivities. In general, key risks include contamination of feedstock, machine downtime, and demand fluctuations. Mechanical performance of pavers depends strongly on plastic type and cleanliness; therefore, robust sorting and washing systems are required. Market risk arises from price volatility and limited local demand; these can be mitigated through public procurement of recycled materials for sidewalks, parks, or tourist zones. Certification of product quality (strength, durability) is also essential to secure buyer confidence.

In summary, a decentralized plastic–sand paver micro-factory represents a technically feasible and socio-economically attractive model for Essaouira. Its relatively modest investment requirements, short payback period, and compatibility with local labor skills make it a promising complement to centralized waste treatment strategies.

Integration of Informal Sector

Section 4 highlighted that the informal sector plays a central yet often overlooked role in waste management in Essaouira. No cooperative currently exists to support them or integrate them into the formal system.

In the context of Essaouira, several integration pathways can be considered:

- **Cooperative Formation**: Informal waste pickers could be organized into cooperatives or associations that offer legal recognition, social protection, and access to training. This would also facilitate collaboration with NGOs, private recyclers, and municipal programs.
- **Participation in Plastic Labs**: Informal actors could be involved in the pilot recycling units proposed above, particularly in roles related to collection, sorting, and pre-treatment. Their experience with material identification and recovery could be an asset to these initiatives.
- **Capacity Building and Toolkits**: Municipalities or NGOs could provide protective equipment, technical training, and entrepreneurial support to improve both the safety and efficiency of informal recycling activities.
- **Inclusion in Plastic Credit Projects**: If a plastic credit mechanism is introduced, the inclusion of informal pickers within a centralized certification scheme (as discussed previously) would be essential to ensure fair benefit-sharing and maximize the social impact of these programs.

To avoid unintended consequences, such integration efforts must be carefully designed in collaboration with the waste pickers themselves. Past experiences show that top-down approaches often fail due to a lack of trust, cultural misalignment, or the disruption of existing income streams (Wilson et al. (2006)). Instead, a participatory planning process, starting with stakeholder mapping, dialogue workshops, and pilot programs, should guide any transition from informality to a more inclusive, formalized role in Essaouira's waste management system.

5.3.2 Intermediate and Centralized Options

Integrated MBT Approach While the options described above present possible intermediate or stand-alone solutions, it is also important to consider a more comprehensive, centralized approach. In Section 6.1, we will investigate the development of a full MBT facility for Essaouira. Such a plant would combine mechnaical sorting and biological treatment pathways. Several biological treatment will be investigated, including anaerobic digestion and Black Soldier Fly processing. This integrated approach could allow for higher overall diversion of waste from landfill, production of valuable outputs (compost, frass, RDF, biogas), and alignment with Morocco's long-term waste management strategy. The MBT analysis will therefore be presented separately and in greater detail in the following section.

Thermal Treatment Pathways

As previously discussed in Section 2.6, modern WtE incineration facilities, especially in Europe, have evolved into clean, highly regulated technologies capable of safely destroying non-recyclable waste while recovering useful energy. In these systems, WtE complements recycling by treating the residual fraction of waste that is too contaminated or composite to be recovered otherwise. However, the implementation of a WtE incineration facility in Essaouira must be carefully assessed. This will be done in this section, based on the Decision Makers' Guide to Municipal Solid Waste Incineration for developing countries (The World Bank, 1999) and by examining key parameters such as waste generation, calorific value, required capacity, and investment costs.

First, the waste generation and supply to the facility should be stable and exceed 50,000 tons per year. Currently, Essaouira only produces around 33,300 tons each year. If we apply the annual growth rate of 2.66% computed in Section 5.2.1, we should obtain 50,000 tons per year in 2041. This could actually arrive sooner if the entire region was included instead of only the city of Essaouira. Nevertheless, this could only take place in minimum 10 years from 2025, approximately.

Next, the lower calorific value (LCV) of the waste is a critical technical criterion for the feasibility of incineration. As The World Bank (1999) stated, a minimum LCV of 7 MJ/kg of waste is required. The LCV can be computed with the following equation:

$$\mathrm{LCV}_{\mathrm{avg}} = \sum_{i=1}^{n} (w_i \times \mathrm{LCV}_i)$$

Where w_i and and LCV_i are the mass fraction and LCV of waste component i. In our case, the mass fraction were presented in Section 2.3.1, in Figure 2, and the LCV for each type of waste was found online (detail in Appendix C). The final LCV is around 7.7 MJ/kg, which is considered sufficient. However, during highly touristic seasons where the share of organic waste raises to around 70%, the LCV becomes too low, which makes it complicated to efficiently run the WtE all year long.

WtE infrastructures also involve substantial upfront investments. Gergel (2015) came up with a formula to estimate the capital expenditure (CAPEX) of a WtE plant:

$$I = 2.3507 \times C^{0.7753}$$

Where I is the investment cost in million USD and C is the annual capacity in thousand metric tons per year (1000 tpa). This brings us to around 49 million USD in initial investment in order to build a WtE plant for Essaouira, assuming a 50,000 ton waste supply.

The potential revenues form the sale of electricity generated can be computed as follow. Using the average LCV of the mixed MSW ($\text{LCV}_{\text{avg}} = 7.39$ MJ/kg, the annual fuel energy equals 102.64 GWh_{fuel}/y. Assuming a net electrical efficiency of 20%, the net electricity export is $E_e \approx 20.53$ GWh/y (i.e., 20,528,000 kWh/y). At a tariff of 0.10 EUR/kWh, this corresponds to about 2.05 million EUR per year in gross electricity revenue. This output is equivalent to the annual consumption of roughly 20,528,000/1,500 ≈ 13,685 households, or 2/3 of Essaouira's homes.

If we annualize the capital investment of roughly 49 million USD (≈45–50 million EUR) over a 25-year lifetime at an 8% discount rate, the annualized CAPEX amounts to about 4.2–4.7 million EUR per year. Adding the OPEX (≈3–4 million EUR/y) (The World Bank, 1999) brings total annual costs to around 7–8.5 million EUR/y. To break even, the plant would therefore require a gate fee in the range of:

$$\text{Gate fee} = \frac{\text{Annualized CAPEX + OPEX - Power revenue}}{\text{Waste treated}} = \frac{(7\text{–}8.5 - 2.05) \times 10^6}{50{,}000} \approx 100\text{–}130 \text{ EUR/t.}$$

Such gate fees would be economically unrealistic in Essaouira's current context. With daily waste generation of about 100 t/d, this would translate into over 4 million EUR per year solely for treatment costs—excluding collection and transport. Although the electricity produced could theoretically power about two-thirds of the city's households, the combination of high capital investment, elevated OPEX, and limited waste quantities renders a stand-alone WtE incineration facility financially unfeasible under present conditions.

Beyond technical feasibility and capital investment, several institutional and contextual barriers also challenge the viability of a WtE incineration plant in Essaouira. As emphasized in the Decision Makers' Guide (The World Bank, 1999), such facilities require a mature and well-regulated MSWM, skilled operational staff, and strong public institutions capable of overseeing environmental standards and long-term financial planning. Currently, Essaouira's MSWM still struggles with fundamental issues such as uncontrolled landfilling, lack of source separation, and weak enforcement mechanisms. The absence of a formal tipping fee system, coupled with the low willingness-to-pay of the population, further limits the ability to finance or maintain such a facility.

Furthermore, WtE technology is typically most effective when integrated within broader regional systems. Larger cities or intermunicipal consortia can benefit from economies of scale and diversified waste streams, making it easier to stabilize calorific values and supply flows. In contrast, Essaouira remains relatively isolated, and its moderate population size and seasonal tourism patterns introduce volatility in waste composition and quantity, which complicates the continuous, stable operation required by incineration plants.

Overall, while WtE could be a technically feasible solution for non-recyclable waste in the long-term, its implementation in Essaouira is not viable under current conditions. The city lacks the waste volume, financial resources, and institutional maturity necessary to sustain such an infrastructure. Regional cooperation or shared infrastructure models could be explored in the distant future, once foundational waste management elements are better in place.

5.4 Improving the landfill

As highlighted in Section 4.4.1, rehabilitating the current landfill is a top priority. The site no longer functions as a controlled disposal facility and has effectively become an open dump, posing serious environmental and health risks. Although there are plans to rehabilitate it, some skepticism remains concerning their feasibility and the fact that it will actually be done. In this section, some recommendations are made to upgrade and rehabilitate the landfill, and they are organized by major operational components. These measures align with ISWA's Landfill Operational Guidelines (2019) and are tailored to Essaouira's context.

5.4.1 Waste Compaction and Cover Application

As was seen in Section 4.4.1, the waste at Essaouira's landfill is dumped without sufficient control, compaction, or cover. This results in rapid loss of landfill space, unstable and fire-prone waste mounds, strong odors, pest infestations, and windblown litter. There is no weighbridge, gate control is minimal, and machinery is very limited.

As an immediate priority, all incoming waste should be directed to a single, defined tipping area, rather than being dumped randomly. Basic gate control must be introduced to record incoming trucks and estimate volumes, using a logbook, since no weighbridge is yet available. Waste should be compacted as it is deposited using any available equipment, such as a bulldozer or loader, with multiple passes to improve stability and density. Simultaneously, operators should begin applying cover soil at regular intervals, ideally daily, but at a minimum weekly. The soil covering should focus first on exposed food waste to deter pests and reduce odors. If soil is limited, tarpaulins or other temporary materials may be used to cover fresh waste overnight. Of course, the implementation of such mechanisms requires additional workforce and machinery. Investments therefore have to be made in order to increase the site's operational capacity, including hiring and training new personnel, investing in compaction and soil spreading equipment, and developing basic infrastructure such as access roads, tipping zones, and soil stockpiles.

Over time, more structured practices should be implemented. This includes acquiring dedicated compaction equipment and applying consistent techniques (e.g. spreading waste in 30–50 cm layers and performing 3–5 compaction passes). A reliable source of cover soil should be secured, either through on-site excavation or partnerships with construction sites. Operators must be trained to apply and compact a daily soil layer of 15–30 cm over the active face, and thicker intermediate cover should be used for areas left unused for longer periods. In the longer run, a weighbridge should be installed to track incoming waste and enforce acceptance rules. The landfill's operations should evolve into a fully supervised system where all waste is compacted and covered systematically, following clear protocols. Cover usage and compaction density should be monitored regularly to ensure effectiveness.

5.4.2 Litter and Vector Control

The current absence of cover and site management at Essaouira's landfill has led to widespread windblown litter and infestations of birds, and feral animals. Strong coastal winds scatter lightweight plastics far beyond the site boundary, while exposed food waste attracts scavengers and creates breeding grounds for pests. These conditions pose health hazards, damage the site's image, and disrupt operations.

As a first step, a rapid cleanup campaign should be launched to collect scattered litter around the landfill and its surroundings. Some (temporary) fencing or netting should be installed downwind of the active tipping area to trap debris. A new fence should also be installed to prevent access from animals or non-authorized people. Pest control measures should begin immediately and should be done by a specialist firm. These actions must be coupled with improved compaction and daily soil cover to remove food access and nesting grounds for pests. Without this, other control efforts will be ineffective.

In the following years, litter and vector control should become routine aspects of landfill operations. Install durable litter fences and assign staff to weekly cleanup patrols along the perimeter and access roads. Maintain rigorous daily cover to suppress pest populations, supplemented by scheduled pest control treatments. Limiting the size of the active tipping area will further reduce the spread of litter and concentration of pests. Over time, these practices should be institutionalized. The landfill should operate with a single, compact, covered working face; fencing and screens should be maintained, and vegetative buffers may be planted to reduce wind, trap litter, and improve site aesthetics.

5.4.3 Informal waste picking

Uncontrolled scavenging at Essaouira's landfill poses serious safety, health, and operational risks. Waste pickers, including potentially minors, access the site freely, working among moving trucks and unstable waste without protective gear. Their activities, while contributing to recycling, can lead to accidents, fires, and increased litter, and should be addressed. Moreover, ISWA 2019 note that scavenging is one of the leading causes of accidents and fatalities at landfills.

The first step is to re-establish control over site access. All entries must be through the main gate, with security personnel recording individuals and restricting access to unauthorized persons. While an immediate ban may not be socially feasible, basic safety measures should be enforced. This includes designating specific areas and hours where pickers can operate safely, away from the working face, and providing protective equipment such as gloves, boots, and reflective vests. Dangerous practices like burning cables must be strictly prohibited.

In the following years, a more structured system for resource recovery should be developed. A small sorting platform near the entrance could serve as a designated area where recyclable materials can be separated in safer conditions. As is planned for the CEV (see Section 4.4.3), existing pickers should be integrated into this system through training or contracts, while further restricting access to the active landfill zone. The perimeter fence should be completed and maintained, with pickers registered. Over time, their presence at the waste face should be phased out, replaced by supervised recovery activities. Reinforcing site security, including gates, fencing, and basic surveillance, will help prevent unauthorized entry and reduce risks like fire or theft.

In the long term, the landfill should operate as a fully secure facility, with no scavenging allowed on the waste itself. Former pickers should be employed in formal recycling programs or other sectors, supported by social reintegration measures. Any material recovery should occur off-site or in controlled zones, not on the tipping face. This aligns with international best practices prioritizing safety, controlled access, and structured waste management. The ultimate goal is a safe, professional landfill operation that values recycling without compromising human health or operational integrity.

5.4.4 Leachate Management

Leachate is currently very poorly managed at Essaouira's landfill, with a malfunctioning drainage system and a lagoon in poor condition. Immediate action is needed to prevent environmental contamination and stabilize the site. As a first step, it is important to clear and repair the existing drainage channels and pipes to allow leachate to flow into the lagoon rather than accumulating in waste. Any stagnant leachate on the surface should be pumped out and transferred either to the lagoon or, if full, to tankers for off-site treatment. Covering waste daily, as recommended earlier, will also reduce rain infiltration and thus leachate production.

In the following years, infrastructure must be improved to ensure consistent collection and partial treatment. Drainage pipes or trenches should be installed at the base of new cells, and existing networks cleaned or repaired. If needed, the lagoon can be expanded or supported by additional evaporation ponds. Low-cost treatment options, such as aerated lagoons or constructed wetlands, could be introduced to reduce organic load. On the longer-term, Essaouira must develop a reliable leachate strategy collection and treatment that remains effective throughout the landfill's life and post-closure period. This includes evaluating whether a more advanced treatment option, such as a modular leachate treatment plant, is feasible. If continuing with lagoon-based storage, it should be optimized as a multi-pond system with periodic sludge removal and permanent monitoring. Ultimately, the best way to reduce leachate is to prevent water from entering the waste, which means investing in a proper final cover system with low permeability. Even after closure, leachate will continue to form and must be collected and treated.

While these actions address the most urgent needs for containing and managing leachate on-site, they remain limited to low-cost maintenance and preventive measures. A more advanced treatment strategy is required to achieve compliance with discharge standards and ensure long-term environmental safety. Detailed engineering solutions for leachate treatment, including a proposed multi-step treatment chain tailored to Essaouira's conditions, are therefore developed and presented later in Section 6.2.

5.4.5 Landfill Closure and Aftercare

Proper closure and long-term aftercare are essential to mitigate the environmental risks of the Essaouira landfill once operations cease. A well-designed closure prevents further leachate formation, reduces uncontrolled emissions, and safeguards surrounding soil and groundwater.

A multi-layer capping system is recommended as a strategic measure to isolate the waste body. This should include a gas venting/foundation layer, an impermeable sealing layer (e.g., HDPE geomembrane or compacted clay), a drainage layer for surface water, and a protective soil and vegetation layer. Such a design minimizes rainwater infiltration, thereby limiting new leachate generation, while also providing erosion protection and restoring the site's landscape function. Long-term maintenance of the cap (repairing erosion, settlement, or cracks) will remain a necessary part of aftercare.

Even after closure, the high organic content of the waste means that landfill gas (LFG) generation will persist for years. To prevent emissions of methane—a greenhouse gas with 28 times the global warming potential of CO_2—appropriate gas management measures must be included in the aftercare strategy. Two main approaches can be envisaged:

- **Active gas well systems**, where vertical wells are drilled into the waste mass to collect LFG for flaring or treatment.
- **Methane Oxidation Layers (MOL)**, where a specially designed soil layer enriched with methanotrophic bacteria promotes biological oxidation of methane into CO_2.

Both approaches have advantages and limitations in terms of efficiency, cost, and operational complexity. Their technical feasibility and expected performance for Essaouira will be investigated in more detail in section 6.3.

Closure must be accompanied by a structured monitoring program to track leachate quality, groundwater protection, and landfill gas emissions. Quantitative environmental protection criteria (EPC) should be established as thresholds to define when the landfill can be considered stabilized and aftercare can be phased out. Monitoring trends—such as declining concentrations of COD, ammonia, or heavy metals in leachate—will guide decisions on whether additional interventions are required.

5.5 Public Engagement and Legal Enforcement

This section presents a combined approach to improving legal enforcement and public engagement in Essaouira's MSWM system. It builds on the diagnostic findings and international best practices reviewed in Chapter 2.6, and is structured around short-term and mid-/long-term interventions. In the short term, the focus lies on enforcing existing laws, improving planning tools, and initiating behavior change through outreach and education. In the longer term, more ambitious legal instruments—such as mandatory source separation, sectoral EPR schemes, and pricing measures—can be introduced alongside deeper societal engagement to drive lasting transformation.

5.5.1 Short-Term Measures: Local Legal Implementation and Enforcement

In the short term, efforts in Essaouira should focus on the effective enforcement of existing legislation and the establishment of local legal instruments and planning tools. Despite Morocco's relatively advanced national waste framework, the diagnostic revealed major implementation gaps at the municipal level, including non-enforcement of the plastic bag ban and littering regulations, and the lack of a formal waste management plan. The following measures aim to operationalize the legal framework already in place and lay the institutional groundwork for more ambitious reforms in subsequent years.

First, the enforcement of the plastic bag ban (Law 77-15) should be strengthened. Although Law 77-15, enacted in 2016, prohibits the production, import, sale, and distribution of plastic bags, fieldwork in Essaouira confirmed their widespread reappearance in markets and shops. Interviews revealed that shopkeepers continue to distribute plastic bags due to consumer preference and the absence of enforcement. To restore the credibility of the law, the municipality should collaborate with national agencies (e.g., Ministry of Interior and the Environment) to conduct periodic inspections. Violators should receive warnings or fines, as was done when the ban was first introduced. Studies have shown that bans on plastic bags are mostly effective when paired with consistent enforcement and viable alternatives for both consumers and retailers (Clapp & Swanston, 2009).

Anti-littering laws should also be enforced, as littering is pervasive in Essaouira, with visible waste accumulation in both central and peripheral areas. Despite this, and current regulations prohibiting littering, no enforcement of these regulations is actually happening. The municipality should thus begin imposing real fines for littering practices. Few years back, a similar situation occurred when the car seat belt became mandatory. People in Essaouira did not care for such regulations and continued to drive without attaching their seat belts. A combination of awareness campaigns and the introduction of continuous fines helped improve the situation and change people's behaviours. This should also be done for littering practices, and MSWM regulations in general.

The municipality should also develop and implement an actual Municipal Waste Management Master Plan. Under Law 28-00 and Law 113-14, municipalities are required to prepare a local waste management strategy. However, as confirmed during field interviews, Essaouira currently lacks any such plan. Developing it should be a priority, as it would serve as a strategic and operational roadmap for the city's MSWM system. The plan should articulate clear goals, define timelines and responsibilities, and identify funding sources. It should also integrate participatory mechanisms to include relevant actors such as local NGOs, informal sector representatives, and private waste operators (in addition to the formal waste collector ARMA). The absence of a structured planning document hinders coordination, prevents access to external funding, and undermines long-term performance monitoring.

In parallel to legal reforms, short-term public engagement efforts are necessary to shift social norms and improve citizen behavior around waste. Current awareness campaigns are limited in scope, reach, and frequency, and remain mostly ineffective among local populations. To address this, the municipality and ARMA should expand their communication strategy beyond seasonal campaigns and prioritize ongoing community outreach.

One effective short-term measure would be the organization of regular school-based awareness programs in partnership with NGOs. Schools are central spaces where early good habits can be shaped, and as seen in Section 2.6, integrating waste education into school life can promote long-term changes. Also, activities such as class discussions, waste sorting demonstrations, and environmental games could be organized on a monthly basis. Teachers should also be trained via basic awareness kits and printed guides.

Additionally, public outreach should be intensified in key areas such as the medina, beaches, and marketplaces, where improper disposal is most visible. Local ambassadors or "eco-volunteers" could be recruited and trained to carry out door-to-door sensitization campaigns, distribute flyers, and collect feedback from residents. In general, awareness campaigns concerning MSWM should be intesified. This also includes the 1% awareness budget legally mandated in ARMA's contract, which should be audited and fully utilized for recurring, measurable campaigns. Reports on outreach activities, including the number of people reached, materials distributed, and participant feedback, should be produced and made public.

5.5.2 Mid-/Long- Term Measures: Regional and Sectoral Legal Strengthening

As Essaouira strengthens its basic governance and enforcement capacities, the period following the short-term improvements offers an opportunity to deepen reform through sectoral legal instruments and regional coordination. Drawing from best practices across Europe and emerging initiatives in Morocco, this phase should prioritize scalable policies such as mandatory separate collection, sector-specific recovery schemes, and pricing instruments to internalize the cost of residual waste. In terms of public engagement, this mid-term phase should mainly consist of consolidating and expanding the efforts initiated in the short term, since long-term success in behavioral change depends not only on information, but also on repeated engagement.

First and foremost, as explained in Section 5.2.3, it is crucial to introduce mandatory separate collection of recyclables and organic waste. Separate collection at source is a foundational element of high-performing MSWM systems in developed countries, as was seen in Section 2.6, and a detailed approached concerning its implementation in Essaouira was covered in earlier section. Overall, it is important to remember that a particular attention should be given to bio-waste separation, as it represents a significant portion of MSW and its separation would improves downstream compost quality but also reduces landfill methane emissions and leachate generation.

Then, PET collection should be scaled up and EPR frameworks introduced. In 2024, the Casablanca–Settat region launched a circular PET roadmap in partnership with UNIDO, aiming to improve traceability, increase food-grade recycled PET (rPET) production, and integrate informal waste pickers into formal collection systems (UNIDO, 2025). The Marrakech–Safi region should draw on this model and develop its own PET collection strategy focused on beverage packaging. Essaouira could serve as one of the pilot cities for the southern coastal region by installing designated PET collection points in hotels, supermarkets, and high-density residential zones, and by engaging informal collectors through registration and training programs. In case the project is a success and that rPET can be utilized for foodpackaging, a DRS scheme could also be introduce to further incentivize PET collection.

This effort could also lay the groundwork for Extended Producer Responsibility (EPR) schemes on packaging. Under EPR, producers are legally responsible for the end-of-life management of the packaging they place on the market. While a national law would ultimately be required, regional pilots can generate early data and institutional experience.

Concerning landfilling, while it remains the dominant form of waste disposal in Morocco, pricing instruments such as landfill taxes have proven effective in reducing waste volumes and shifting materials toward recycling and recovery in Europe, as highlighted in Section 2.6. Therefore, in Morocco, a modest regional landfill tax could be introduced for all untreated MSW entering landfills. To ensure social and political acceptability, the tax could exempt treated fractions such as inert residues, and its revenues could be earmarked for visible public benefits such as composting infrastructure, improved landfill sites, or waste education programs. While such fiscal measures require careful planning and coordination, they represent an essential tool for aligning financial incentives with the waste hierarchy.

Together, these mid-term legal instruments aim to expand responsibility beyond municipal services and engage producers, consumers, and businesses in a more circular and collaborative waste system. However, their implementation obviously requires foundational improvements to already be in place. For example, the successful rollout of separate collection or a landfill tax presupposes that the landfill has been rehabilitated, that sorting and treatment infrastructure is operational, and that reliable data systems are in place to track waste flows and compliance. Nevertheless, by testing scalable reforms and aligning with national and international standards, Essaouira and the Marrakech–Safi region could position themselves as frontrunners in Morocco's ecological transition.

6 Strategic Phase — Practical Engineering Solutions for MSWM in Essaouira

While Chapter 5 defined strategic priorities for the improvement of Essaouira's MSWM system, this chapter translates selected recommendations into practical engineering designs. The aim is to demonstrate how technical solutions could be implemented on the ground, with indicative sizing, process flows, input–output balances, and order-of-magnitude costs.
Three critical interventions are examined in detail:

- The design of a Mechanical–Biological Treatment (MBT) facility with several biological process propositions for organic waste treatment, positioned as the central infrastructure for the planned CEV.
- A treatment chain for landfill leachate, addressing urgent environmental and health risks identified during field observations.
- Options for landfill closure and gas management, including methane oxidation layers and gas well systems, to mitigate greenhouse gas emissions and extend site safety.

By moving from strategic orientation to engineering feasibility, this chapter provides concrete evidence that the proposed transition toward a more sustainable MSWM system in Essaouira is not only desirable, but technically achievable.

6.1 Mechanical–Biological Treatment (MBT) Plant Design

MSW in Essaouira is currently disposed of entirely at the landfill without prior treatment, leading to rapid consumption of landfill space, uncontrolled emissions, and the loss of recoverable resources. To address these challenges, the planned CEV offers an opportunity to integrate an MBT facility as the core infrastructure of the future system. Such plant combines mechanical sorting of mixed waste with biological stabilization or valorisation of the organic fraction, thereby reducing the volume of waste requiring final disposal while recovering valuable materials and energy. Given that more than half of Essaouira's waste stream consists of organics, this study investigates the integration of some biological treatments, with anaerobic digestion (AD) or black soldier fly (BSF) integrated in the plant. This section develops a conceptual MBT design adapted to Essaouira's waste characteristics, including the process chain, expected mass flows, indicative equipment sizing, and order-of-magnitude cost estimates. Design choices and parameter ranges in this subsection are primarily informed by the EU Best Available Techniques Reference Document for Waste Treatment (*WT BREF*, 2018) and standard texts (Tchobanoglous & Kreith, 2002; Worrell & Vesilind, 2012).

6.1.1 Waste Input and Composition

We consider an MBT facility processing 85 tons of mixed waste per day for the municipality of Essaouira (increasing to 110t in summer months), to which are added an estimated 25 daily tons from neighbouring municipalities. The MBT should thus be able to process a total of around 40 kt per year, with daily quantities going up to 150 tons. The waste composition is approximately: 61% organic (biodegradable) material, 9% plastics, 9% fine inert particles ($<$20 mm), 5% paper/cardboard, 5% textiles, 2% glass, 1% metals, with the remainder being miscellaneous wastes. The final goal is to maximize recovery of organics for stabilization, recover recyclables, produce a refuse-derived fuel (RDF) from high-calorific residues, and minimize landfill disposal.

6.1.2 Mechanical Pre-Treatment and Separation

Waste Reception and Pre-sorting:

The MBT process begins with a sequence of mechanical sorting operations designed to separate the incoming mixed waste into distinct fractions for further treatment. Upon arrival at the facility, waste is first unloaded onto a tipping floor, where large or hazardous items are removed manually as a precautionary step. Involving manual labour at this stage prevents damage to machinery by removing bulky items such as tyres or scrap metal, and it also allows recovery of oversized recyclables that would otherwise be lost in the system. From the tipping floor, a front-end loader feeds the waste into the initial pre-treatment line, ensuring a controlled and continuous flow into the downstream equipment. Here, to handle the arrival of the approximate daily 110 tons, two to three employee are required in order to receive the waste, feed the treatment line, and spot/pick the bulky and hazardous waste. After this first stage, the waste composition and quantity are assumed to remain essentially unchanged, as bulky items are relatively uncommon due to the use of communal containers for initial waste disposal.

Bag Opening:

In many European MBT facilities, the first mechanical step following reception is a slow-speed shredder or bag opener designed to homogenize the waste and ensure that plastic bags are opened (*WT BREF*, 2018). Such machines reduce the waste to a manageable size (typically <300 mm) and liberate organic matter from closed bags, allowing for more efficient downstream separation. For plants of the size required in Essaouira (10-15 tons/hour throughput), a shredder of 200-250 kW would typically be installed. However, this type of machinery is quite costly, and represents a non-neglectable investment with additional operation and maintenance costs linked to energy consumption and wear of cutting teeth.

In the context of Essaouira, however, MSW is not discarded in tied plastic bags but rather deposited directly from household buckets into communal containers. As a result, intact bags are relatively uncommon, and the need for a dedicated shredder is less critical. A cost-effective alternative would therefore be to rely on manual opening of the occasional bags, performed by one to two workers at the reception or on the infeed belt. This approach significantly reduces capital expenditure and maintenance requirements, while still ensuring that waste enters the subsequent screening equipment in a free-flowing form. This choice depends on available investment and occupational health considerations, but for Essaouira, manual bag opening appears more appropriate given the current waste disposal practices.

Primary Screening (<80 mm):

After bag opening, the waste stream is conveyed to a rotating drum screen (trommel) fitted with holes of 80 mm. The trommel separates the material into two fractions based on particle size. An 80 mm mesh size is a common cut in MBT facilities, as it efficiently captures the "wet" organic-rich fraction while producing a "dry" coarse fraction suitable for RDF production (Banks et al., 2010). Similar performance can be anticipated under Essaouira's waste composition.
The fine fraction (<80 mm) is generally very rich in organic material. Out of the 110 tons of waste arriving to this first separation step, around 70% of the waste ends up in the fine fraction, which is expected to contain the majority of the 61% biodegradable material in Essaouira's MSW, the additional very fine fraction (<20 mm like sand, glass shards, grit), and some small paper and plastic fragments and moisture. Due to the presence of the very fine inert material representing around 9% of the total waste input, this fraction is sent to a secondary fines screening.
The oversized fraction (>80 mm), or remaining 30%, consists mainly of non-organic, high-calorific components such as plastics, textiles, cardboard, and occasional pieces of wood or larger organic fragments that did not break down. This coarse fraction is transferred to a sorting line for the recovery of recyclables (metals, plastics, cardboard) and the preparation of RDF.

Secondary Fines Screening (<20 mm):

This step separates ultrafines fraction from the organic waste using a flip-flow vibrating screen with 20 mm apertures. The <20mm fraction is mostly inert dirt and glass that has little biological or fuel value. Moreover, if retained, the fines can contaminate the organic stream and negatively affect the efficiency of subsequent biological treatment processes. Therefore, they are separated out for landfill. This represents 9% of the initial waste input, or around 10 000 kg per day.
The 20–80 mm remaining fraction (cleaner organic-rich material), totaling around 67 tons, proceeds to biological treatment. Overall, this two-stage screening helps achieve around 95% organic recovery (Shyamal et al., 2024).

Ferrous and Non-Ferrous Metal Removal:

The waste stream continues its journey on a conveyor belt and ferrous and non-ferrous metals are removed from the >80 mm oversize stream to recover recyclable materials and protect downstream processes. To ensure effective separation, the material is evenly spread on the belt using a leveling roller and metering device, keeping the burden depth below 80–100 mm. Then, a cross-belt magnet extracts ferrous metals such as cans, iron pieces, and steel fragments. This simple unit operates at the conveyor throughput of approximately 10–15 t/h. For such throughput, the conveyor belt should operate under the overband magnet at a speed of approximately 0.15 m/s, ensuring an optimal burden depth (80 mm thickness) and effective ferrous metal separation. This step should recover close to 1 ton of metal daily, which consists of round 3% of the incoming waste ($\approx$ 33 tons after both screenings). An eddy current separator can be installed downstream of the magnet to recover non-ferrous metals such as aluminum cans or other aluminum components.

Sorting of Recyclables from Overs:

The remaining oversize fraction consists mainly of plastics, paper/cardboard, and textiles, and can be subjected to a sorting line to recover valuable recyclables. In the case of Essaouira, manual sorting is considered the most appropriate approach. Labour is relatively affordable and, importantly, there is a large community of informal

waste pickers with extensive practical knowledge of identifying and extracting recyclables. Integrating these workers into the formal system not only provides social and economic inclusion, but also leverages their existing expertise, thereby reducing the need for extensive training. Manual sorting also provides greater flexibility than automated systems, as workers can recover materials present in low quantities or those difficult to distinguish mechanically. For safety and efficiency, the sorting line should be enclosed and ventilated, and all workers should be equipped with adequate protective gear. At this stage, the remaining waste to process is around 32 tons, which makes it very feasible for a manual sorting line. A throughput of around 5 t/h, and a 1.0–1.2 m belt running with 50–80 mm burden can be staffed by six pickers (three per side) plus a line lead and baler operator. With rotation and breaks this equates to 10–11 rostered staff per shift, ensuring safe, flexible recovery of PET/HDPE, cardboard and textiles while integrating experienced informal pickers into formal operations.
The quantity of waste separated through this step is not equal to the initial plastic/textile/cardboard quantities, as it is assumed only some cardboard and rigid plastic are of good enough quality to be picked out. Indeed, given the mixed nature and high contamination of the incoming waste, much paper/plastic is dirty and may not meet recycling quality. Therefore, we assume a recovery of around 3 to 5% of the initial input, or 3.3 to 5.5 tons. The allocation of the 3.3-5.5 t/d of recovered recyclables among plastics, cardboard/paper, and textiles was estimated using salvageability factors, with the recovered weight of each material i calculated as:

$$W_i = \frac{S_i \times P_i}{\sum(S_j \times P_j)} \times W_{\text{total}}$$

where P_i is the proportion of material i in the initial waste composition, S_i its salvageability factor, and W_{total} the total recovered recyclables. Applying $S_{\text{plastics}} = 0.60$, $S_{\text{cardboard}} = 0.25$, and $S_{\text{textiles}} = 0.15$ yields approximately 73% plastics (2.4–4.0 t/d), 17% cardboard/paper (0.56–0.93 t/d), and 10% textiles (0.33–0.56 t/d).

Lightweight Fraction Separation (Wind-Sifter):

Coming out of the manual sorting of recyclable is a ≈ 26.5-29 tons waste stream composed mainly of light, high calorific waste suitable for RDF production, and heavy, non combustible items such as glass, stone or ceramic residues. To strip the residual films and ultralight contaminants from the >80 mm overs without prior shredding, the oversize stream is routed under a negative-pressure wind-sifter (e.g., Nihot SDX), which ejects dense inerts (stones, glass, ceramics) as a heavy reject while conveying the light, predominantly combustible fraction (paper, films, light plastics, textiles) to RDF preparation. This configuration —widely applied in RDF/SRF plants— reduces ash and protects the downstream shredder. The unit comprises a high-efficiency fan, separation drum and expansion/settling chamber, which is appropriate for the Essaouira line (4 t/h).Typical operating settings are a belt speed of 2–4 m/s (upper end improves trajectory control) and a process air speed of 2 m/s (Nihot Recycling Technology B.V., n.d.).
The infeed to this separation step is the >80 mm overs after manual sorting, ≈ 26.5 - 29t. Using the intial waste composition derived from Figure 2 and upstream recoveries, we can estimate the composition of the incoming waste 26.5t waste stream as such: 6.80 tons of plastics, 4.75 tons of paper/cardboard, 5.1 tons of textiles, 2.2 tons of glass, 4.4 tons of initial not-classified (NC) non-combustible waste (stones/ceramics), 1.1 ton of NC combustible (wood/rubber), and 2.15 tons of other residuals . The wind-sifter is operated in RDF mode with per-class light split factors $f_{\text{light},i}$ reflecting density/shape. The light split factor for each type of waste was assumed as such: plastics 0.85; paper/cardboard 0.90; textiles 0.85; glass 0; NC 0.10; Comb–NC 0.70; others 0.50. We can then compute:

$$W_{\text{light},i} = f_{\text{light},i} \times W_i, \qquad W_{\text{light}} = \sum_i W_{\text{light},i}, \qquad W_{\text{heavy}} = W_{\text{in}} - W_{\text{light}}.$$

Table 18: Wind-sifter split (RDF mode) for the >80 mm overs at 26.5 t/d infeed (user-selected split factors).

Class	In (t/d)	Split to light (%)	Light (t/d)	Heavy (t/d)
Plastics	6.80	85	5.78	1.02
Paper/cardboard	4.75	90	4.28	0.48
Textiles	5.10	85	4.34	0.77
Glass	2.20	0	0.00	2.20
NC (stones/ceramics)	4.40	10	0.44	3.96
Comb–NC (wood/rubber)	1.10	70	0.77	0.33
Others (moisture/mixed)	2.15	50	1.08	1.08
Total	**26.50**	–	**16.68**	**9.83**

Thus, at 26.5 t/d infeed the wind-sifter yields ∼16.68t/d light (RDF feed) and ∼ 9.83 t/d heavy (inert reject). Scaling the same composition and split factors to 29t/d gives around 18.25 tons of light and 10.75 tons of heavy.

Residuals and RDF Preparation (Shredding + Baling):

After extracting recyclable materials and non-combustible waste, the waste stream is left with and RDF feed of approximately 16.5 to 18.5 tons, which can be used for off-site energy recovery (e.g., cement kilns).
In order to meet cement-kiln handling requirements and ensure consistent combustion, a dosing bunker with metering belt feeds the RDF fraction to a single-shaft, slow-speed shredder equipped with an interchangeable screen targeting $\leq 50mm$ output. The design throughput should comfortably handle daily peaks and short operational windows; with 16.5-18.5 t/d over an 8 h shift, the average load is only 2 t/h, but the shredder should be sized for 4-6t/h to account for potential surges and maintenance. Shredding is placed after metal removal and manual sorting so as to (i) preserve recyclables, (ii) minimize wear from metal contamination, and (iii) avoid generating excess fines. Target operating limits for the RDF feed are moisture $< 25\%$ (preferably $< 20\%$).
The shredded RDF is then compacted using a horizontal channel baler (press force $\geq$60–80 t). This baler is shared with the recyclables bay but operated in dedicated campaigns. Typical RDF bales are $\sim$1100$\times$750$\times$1100 mm at 400–600 kg/m^3, which yields 0.40–0.60 t per bale. For 16.5-18.5 t/d RDF, this corresponds to 30-40 bales/-day. A three-day buffer to handle shipping therefore requires floor space for $\sim$60–120 bales (segregated from recyclables), plus a forklift and covered storage to prevent re-wetting.
The RDF's lower heating value is expected to be around 14 MJ/kg (*WT BREF*, 2018), representing around 230-260 GJ per day, or approximately 63-72 MWh.

Additional ancillary systems are assumed here as well. Conveyors link the residual oversize bunker to the shredder, baler, and storage bays; dust extraction is provided at transfer points and the shredder hopper. Standard handling equipment (forklift/front-end loader) manages bale movements, and a weighbridge records outbound RDF tonnage for mass balance and invoicing. These ancillary systems are considered included in the conceptual design and cost estimates.

Mass Flow Summary:

At the end of the mechanical pre-treatment stage, the daily mixed waste stream of 110 tons is partitioned into four main outputs (Figure 36). Around **61%** of the input is recovered as **organic-rich fines** suitable for biological treatment (AD/BSF), while **15–16%** forms a **combustible fraction** that can be prepared as RDF. **Recyclables** account for about **4%** of the input, mainly rigid plastics, cardboard and textiles, and close to **1% of ferrous and non-ferrous metals** are separated. The **residual 18.5%** consists of ultrafines and heavy inert rejects, which are directed to landfill. This configuration achieves a substantial diversion of biodegradable and recyclable materials away from direct disposal, creating stable feedstocks for both valorisation and energy recovery.

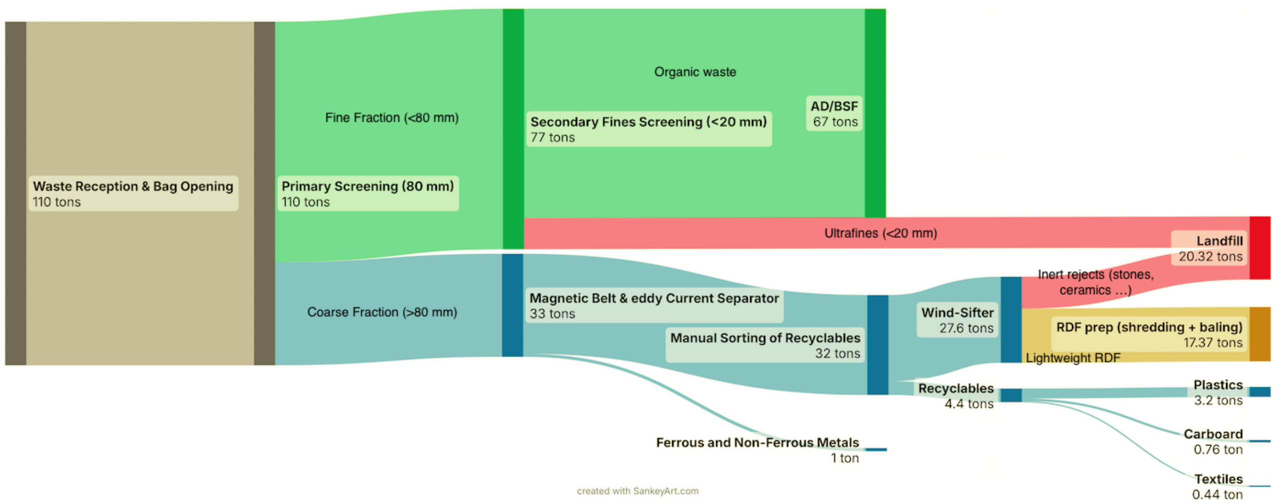


Figure 36: Mass Flow Diagram of Mechanical Pre-Treatment and Separation

6.1.3 Biological Treatment of Organic Fraction

Given the very high organic content ($\sim$61%) retrieved in the waste, the separated fine fraction (roughly 67 t/d) will undergo biological treatment to stabilize it and recover value. Two alternative biological processing options are considered, each with its advantages: anaerobic digestion (AD) and black-soldier fly (BSF) composting.

The computations and assumptions in this section were derived from lecture notes of Professor Merle de Kreuk (2024), as part of the reactive resources and waste module of the 2023-2024 Environmental Engineering Master.

Option A: Anaerobic Digestion (Biogas Production)

AD offers a robust pathway to stabilize the high organic content of Essaouira's waste while recovering energy. In this option, the screened organic fines (67 tons/day, or 24,500 t/year) are fed to sealed digesters where microbes convert biomass into biogas and a nutrient-rich digestate. Two types of AD are considered here: wet AD Continuous Stirred Tank Reactors (CSTR) , where organics are conditioned into a pumpable slurry (∼10% Total Solid (TS)) and continuously mixed and fed; and dry AD (plug-flow/garage type), where organics remain stackable (20–35% TS) and are treated in high-solids reactors with percolate recirculation.

In order to design each solution, some baseline assumption are made to compute for the sizing and mass flow of each type of AD:

- **Throughput**: 67 t/d sent to biological treatment.
- **Feed properties:** $TS_{in} = 28\%$, VS (Volatile Solids)/TS = 85%.
- **Front-end rejects:** 5% of wet mass (plastics + grit/glass) removed before AD to protect equipment; excluded from AD mass balance.
- **Process temperature:** 35 °C (mesophilic AD).
- **Hydraulic/Solids retention time (HRT/SRT):** 25 days (correlated to temperature).
- **Methane yield factor:** 0.45 m^3 CH_4 per kg VS destroyed (stoichiometric/BMP basis).
- **Biogas composition:** 60% CH_4 / 40% CO_2 (by volume).
- **VS destruction efficiency (base case):**
  - Wet AD: 60% of incoming VS.
  - Dry AD: 55% of incoming VS.
- **Wet AD–specific assumptions:**
  - Target digester slurry TS: 10%
  - Slurry density: ∼1,000 $kg{\cdot}m^{-3}$.
  - Feed particle size after maceration: ≤20-30 mm.
  - Organic loading rate (design check): ∼2.0-3.5 kg $VS{\cdot}m^{-3}{\cdot}d^{-1}$.
- **Dry AD–specific assumptions:**
  - Reactor feed TS (stackable): ∼25% after minimal conditioning.
  - Packed bulk density in reactor: ∼0.75 $t{\cdot}m^{-3}$ (wet basis).
  - Percolate recirculation for moisture/heat; no slurry equalization tank.
- **Energy conversion reference (for later):** 1.8–2.0 kWh_{el} per m^3 biogas in CHP (net), with a similar magnitude available as useful heat (for heat balance checks).

These assumptions allow us to compute, for each route: (i) pre-AD mass splits, (ii) digester working volume , (iii) biogas/CH_4 outputs from VS destroyed.

Wet AD:

Before organic fines can be fed into wet anaerobic digesters, a series of pretreatment steps is required to convert the screened material into a stable, pumpable slurry and to remove disruptive contaminants. The sequence typically consists of four main stages:

1. **Slurry preparation:** The organic fraction is mixed with process water or, preferably, recycled digestate to reach a target total solids content of ∼10%. This step is carried out in a hydraulic pulper or slurry tank, ensuring the waste becomes pumpable and suitable for downstream handling.

2. **Grit and heavy fraction removal:** A hydrocyclone or compact grit trap removes sand, glass, and small stones that would otherwise cause abrasion and sedimentation in the digester. Design provisions usually include a grit sump of $\sim 2\text{m}^3$, providing one week of storage at expected accumulation rates (0.2–0.3m^3/d), with easy access for periodic clean-out.

3. **Floatables removal:** Lightweight plastics and films that escape initial screening are skimmed off at the slurry surface. This can be achieved by a simple skimming device or, where available, a low-cost flotation step with air injection. The objective is to avoid floating layers in the digester that impair mixing and reduce effective volume.

4. **Equalization tank and maceration:** The pretreated slurry is collected in an equalization (EQ) tank, which dampens fluctuations in flow and solids concentration over the day. Digestate recirculation is used to fine-tune TS, with minor freshwater addition if needed. A slow-speed mixer maintains homogeneity, while an inline macerator reduces particle size to ≤20–30 mm, protecting pumps and ensuring reliable digester hydraulics. For Essaouira's case, with 63.6 t/d (rejects removed in previous steps) feed at 28% TS (17.8 t TS/d), dilution to 10–12% TS yields a slurry flow of 150–190 m^3/d. Following a standard design rule of 8h residence time, an EQ tank volume of 75–100 m^3 (plus 10–20% freeboard) is recommended.

After pretreatment and equalization, the homogenized slurry is pumped to the digesters as a continuous feed using low-shear, solids-tolerant pumps. The design basis is mesophilic operation at 35 °C and an HRT of 25 days.

For the conservative case of 10% TS slurry, the average feed flow is taken as $Q \approx 188$ m^3/d. The required working volume is:

$$V_w = Q \times \text{HRT} = 188\ \text{m}^3/\text{d} \times 25\ \text{d} \approx 4{,}700\ \text{m}^3.$$

With an incoming volatile solids load of ∼15,900 kg VS/d, the OLR is:

$$\text{OLR} = \frac{15{,}900\ \text{kg VS/d}}{4{,}700\ \text{m}^3} \approx 3.4\ \text{kg VS} \cdot \text{m}^{-3} \cdot \text{d}^{-1},$$

which falls within the targeted design window of ~ 2.0–3.5 kg VS·m^{-3}·d^{-1} for wet CSTRs.

To provide redundancy and maintenance flexibility, two digesters are proposed, each sized for ∼60% of the total working volume:

$$V_{w,\text{per tank}} \approx 0.60 \times 4{,}700 \approx 2{,}800\text{-}3{,}000\ \text{m}^3.$$

Allowing 10-20% headspace for gas and foam, the geometric volume per tank is on the order of 3,600 m^3.

Feed pumps should handle ≤20–30 mm particles and 10–12% TS.

Raising the daily feed from around 20 °C to 35 °C requires:

$$E \approx m\, c_p\, \Delta T = (188{,}000\ \text{kg/d}) \times 4.18\ \text{kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1} \times 15\ \text{K} \approx 11{,}800\ \text{MJ/d} \approx 3.3\ \text{MWh/d}.$$

This duty should be covered by the CHP thermal output, with margin for losses.

The biogas production is estimated from the destroyed VS, the methane yield per kg VS destroyed, and the methane fraction in biogas:

With $\text{VS}_{\text{in}} \approx 15{,}900$ kg VS/d, VS destruction $\eta_{\text{VS}} = 60\%$, and yield $Y_{CH_4} = 0.45\ \text{m}^3\ \text{CH}_4/\text{kg VS}_{\text{destroyed}}$:

$$\dot{V}_{CH_4} = \big(15{,}900\big) \times 0.60 \times 0.45 \approx 4{,}300\ \text{m}^3_{CH_4}/\text{d}.$$

Assuming $x_{CH_4} = 60\%$ (typical for OFMSW), total biogas is:

$$\dot{V}_{\text{biogas}} \approx \frac{\dot{V}_{CH_4}}{x_{CH_4}} \approx \frac{4{,}300}{0.60} \approx 7{,}200\ \text{m}^3/\text{d}\ (\approx 300\ \text{m}^3/\text{h}).$$

Here, we can see that the buffer of 10-20% in the digestate tank from earlier is enough to cover around 2 hours of biogas production. The biogas is then conditioned (cooling, dewatering) and fed to a combined heat and

power (CHP) unit to generate electricity (with simultaneous heat recovery).
Using 1.8-2.0 kWh_{el} per m^3 biogas (net), daily electricity is:

$$E_{el} \approx 7{,}200 \times (1.8\text{–}2.0) \approx 13.0\text{–}14.4 \text{ MWh}_{el}/\text{d}$$

which corresponds to an average export of ∼0.54–0.60 MW after parasitics.
In terms of heat output, this is of comparable magnitude (often slightly higher) than electricity. Conservatively:

$$E_{th} \approx 12\text{–}16 \text{ MWh}_{th}/\text{d}.$$

This comfortably covers the estimated 3.3 MWh/d required to raise the feed from 20 °C to 35 °C, leaving a surplus of ∼9–13 MWh_{th}/d for maintaining digester temperature and potential low-grade heat uses (e.g., RDF or digestate drying).
To summarize, we obtain $\dot{V}_{\text{biogas}} \approx 7{,}200$ m^3/d (∼300 m^3/h); $E_{el} \approx$ 13–14.4 MWh/d (∼0.54–0.60 MW); $E_{th} \approx$ 12-16 MWh/d; process heat demand ≈3.3 MWh/d (covered with margin).

After the digestion process, we are left with some solid matter called digestate. Assuming TS_{in} = 18.8t/d made of 3.0t/d ash/inerts (15% of TS) and 15.9 t/d VS, with 60% VS destruction:

$$\text{VS}_{\text{remaining}} = 15.9 \times (1 - 0.60) \approx 6.4 \text{ t/d}, \qquad \text{TS}_{\text{out}} \approx 3.0 + 6.4 = 9.4 \text{ t/d}.$$

Digestate is dewatered by centrifuge to a target cake of ∼25% TS:

$$\text{Cake mass} \approx \frac{9.4 \text{ t TS/d}}{0.25} \approx 38 \text{ t/d (wet)}.$$

The centrate (filtrate) is routed back to the EQ tank as dilution/inoculation, closing the water loop and stabilising TS for wet-AD operation.
The dewatered digestate ("cake") can be used for landfill operational cover and site rehabilitation. Where quality standards for contaminants and hygiene are met, it may also be applied as a fertilizer in agriculture.

Figure 37 summarizes this process. Organic fines (63.6 t/d at 28% TS) are diluted with digestate/fresh water to a 10–12% TS slurry, polished for grit and floatables, equalized/macerated, and fed continuously to two mesophilic CSTRs (HRT 25 d). The digesters then yield 7,200 m^3/d biogas (300 m^3/h, 60% CH_4) conditioned and buffered to CHP (13–14.4 MWh/d electricity, 12–16 MWh/d heat), while digestate is dewatered to 38 t/d cake at 25% TS with filtrate recycled to the EQ tank.

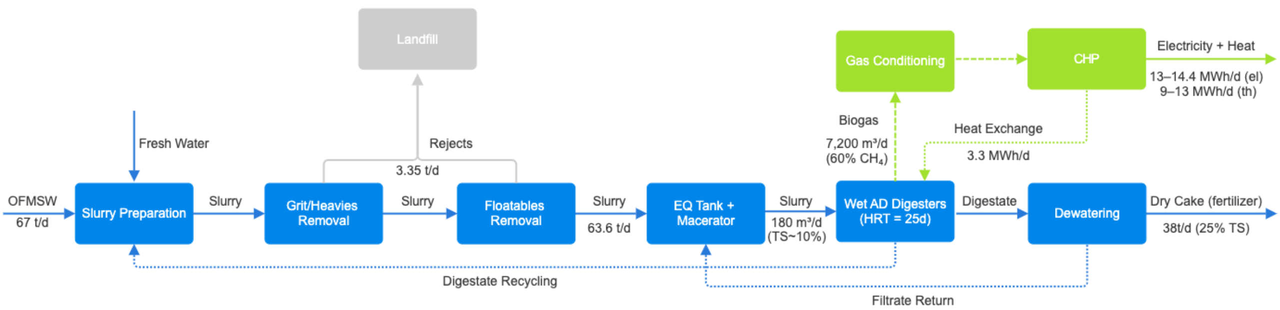


Figure 37: Wet AD process flow for OFMSW

Dry AD:

In dry AD, the organic fraction is treated at high solids content (20-35% TS), eliminating the need for extensive dilution. Instead of a pumpable slurry, the feed is prepared as a stackable material, with percolate recirculation providing moisture balance and inoculation. Two reactor configurations are common: horizontal plug-flow digesters and batch "garage" tunnels with staggered operation. The process is described in four main stages:

1. **Pretreatment:** Given that the stream is already loose OFMSW (post 80/20 mm screening), pretreatment focuses on coarse contraries. A simple air-knife for lightweight plastics removes residual films and clumps. A grit sump at the feed bay intercepts glass and stones. With 5% rejects, approximately 3.35 t/d are removed (split 50/50 films vs. grit). No dilution is applied, keeping the feed within 20–35% TS.

2. **Reactor feeding and percolation:** The conditioned OFMSW is loaded directly into the digester(s) at ∼25% TS. Percolate recirculation maintains uniform moisture, redistributes heat, and enhances contact between substrate and microbial populations. Unlike wet AD, no equalization tank is needed.

3. **Anaerobic digestion:** The reactors operate under mesophilic conditions at 35 °C with a solids retention time of 25 days. Options include (i) two parallel plug-flow digesters (1,050–1,100 m^3 each), or (ii) four garage-type batch tunnels (530 m^3 each) with staggered loading. A percolate tank of ∼210 m^3 (10% of digester volume) provides recirculation capacity.

4. **Digestate handling and post-treatment:** At the outlet, digestate is stackable and partially stabilized. A short post-aeration step (2-4 weeks) improves odor and stability, while also drying the material to ∼35% TS. A 10-20 mm screen can be used to remove residual plastics or oversized fragments, which are diverted to RDF or landfill.

Starting from 67 t/d feed, 5% front-end rejects (3.35 t/d) are removed, leaving 63.65 t/d to the digester. The reactor feed thus contains:

$$\text{TS}_{\text{reactor}} = 17.82 \text{ t/d}, \qquad \text{VS}_{\text{reactor}} = 15.15 \text{ t/d}, \qquad \text{Water} = 45.83 \text{ t/d}.$$

This corresponds to ∼28% TS, comfortably within the dry AD operating range.
With a bulk density of 0.75 t/m^3, the volumetric feed is:

$$Q \approx \frac{63.65}{0.75} \approx 84.9 \text{ m}^3/\text{d}.$$

For an SRT of 25 days, the total volume shoud be:

$$V_w = Q \times \text{SRT} \approx 84.9 \times 25 \approx 2{,}120 \text{ m}^3.$$

Assuming 55% VS destruction, the biogas production is the following:

$$\text{VS}_{\text{destroyed}} = 0.55 \times 15.15 \approx 8.33 \text{ t VS/d}.$$

The methane generation is:

$$\dot{V}_{CH_4} = 8{,}330 \text{ kg VS/d} \times 0.45 \frac{\text{m}^3}{\text{kg VS}} \approx 3{,}750 \text{ m}^3_{CH_4}/\text{d}.$$

With $x_{CH_4} = 60\%$, the total biogas yield is:

$$\dot{V}_{\text{biogas}} \approx \frac{3{,}750}{0.60} \approx 6{,}250 \text{ m}^3/\text{d} \ (\sim 260 \text{ m}^3/\text{h}).$$

Allowing for 50–60% VS destruction, the range is 5,680–6,820 m^3/d.
Using 1.8–2.0kWh_{el} per m^3 biogas, the net electricity production is:

$$E_{el} \approx 6{,}250 \times (1.8\text{–}2.0) \approx 11.2\text{–}12.5 \text{ MWh}_{el}/\text{d},$$

equivalent to ∼0.47–0.52 MW. Thermal output is of similar magnitude (∼11–14 MWh_{th}/d), typically sufficient for digester/percolate heating and post-treatment needs.
Then, the non-biodegradable fraction consists of ∼2.67 t/d ash/inerts and ∼6.82 t/d residual VS, giving $\text{TS}_{\text{out}} \approx$ 9.49 t/d.
After air-drying to 35% TS, the wet digestate is:

$$\text{Digestate (wet)} \approx \frac{9.49}{0.35} \approx 27.1 \text{ t/d}.$$

Post-screening removes 0.3–0.8 t/d of plastics or fragments to RDF/landfill, while the stabilized digestate may be applied for land reclamation or, if meeting standards, as compost-like output.

Figure 38 summarizes the dry AD process. Organic fines (67 t/d) are pretreated to remove ∼5% rejects (films and grit), yielding 63.65 t/d feed at 28% TS. The material is loaded into two plug-flow or four garage-type digesters ($V_w \approx$ 2,120 m^3, SRT 25 d), with percolate recirculation for inoculation. Biogas production is 6,250 m^3/d (3,750 m^3/d CH_4), corresponding to 11.2–12.5 MWh/d electricity and ∼11–14 MWh/d heat. Digestate output is ∼27 t/d at 35% TS after post-aeration and screening.

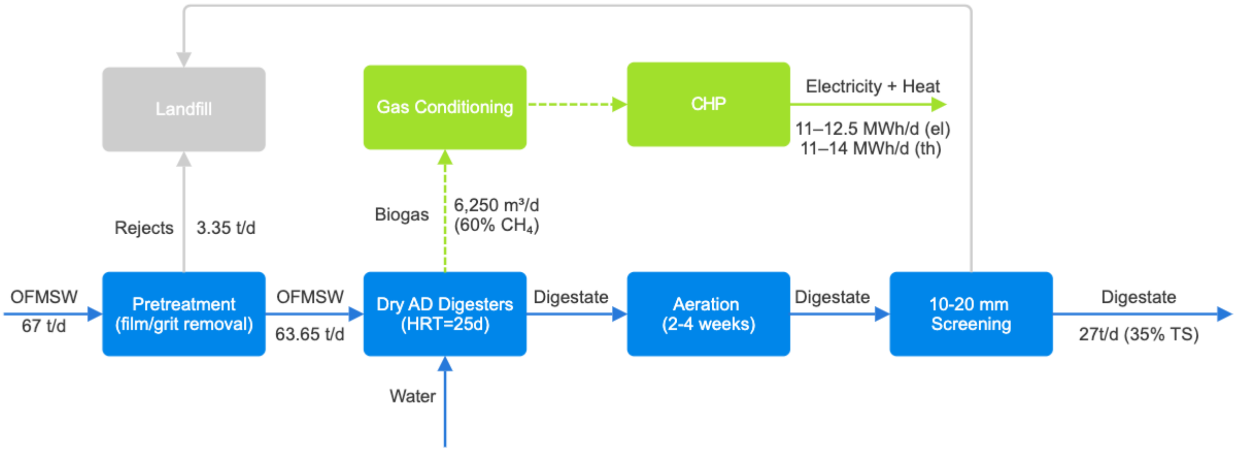


Figure 38: Dry AD process flow for OFMSW

Option B: Black Soldier Fly (BSF) composting:

Black Soldier Fly (BSF, Hermetia illucens) composting has emerged as a promising technology to treat OFMSW, particularly in low- and middle-income contexts. BSF larvae (BSFL) are capable of reducing the wet mass of biowaste by 60–80% within a 12-day cycle while converting 15–25% of the substrate into high-protein, high-fat larvae biomass. The residue (frass) can be further stabilised by composting, vermicomposting, or anaerobic digestion.
Unlike anaerobic digestion or composting, few publicly documented full-scale BSF facilities exist at throughputs above 50 t/d. Some projects and reviews cite facilities treating between 60 and 200 t/d, but technical details (layout, equipment, performance data) are often unpublished. Therefore, a precise facility design for Essaouira cannot be replicated directly from literature. Instead, indicative flows and requirements can be estimated using basic data (Dortmans et al., 2017) and Eawag's model (2017), as well as scaling projections (Zurbrügg et al., 2018).

In the MBT concept for Essaouira, 67 t/d of OFMSW (20–80 mm fraction) is available. Assuming 5% rejects (plastic, glass, stones), around 63.6 t/d can enter the BSF line. Moisture should be kept between 70-80%, which is in accordance to previous assumptions that Essaouira's OFMSW has a TS concentration of 28% (72% water). Using the Eawag BSF costing tool (Eawag, 2017) with the parameters shown in Figure 39 (BSFL/waste = 0.25; residue/waste = 0.20), the expected daily outputs are:

- **Live larvae (wet):** ~15.8 t/d (≈5,749 t/year).
- **BSF meal:** ~2.8 t/d (≈1,035 t/year).
- **Residue (frass, wet):** ~12.6 t/d (≈4,599 t/year), requiring stabilisation/composting.
- **Rejects:** ~3.2 t/d to landfill.

At harvest, larvae can be sanitised (blanching), dried (<10% moisture), and further processed into protein meal, and to extract oil.

Performance of BSF processing	
Amount	Unit
12	days of treatment (MRT)
0,025	grams of dry feed/larva/day
0,05	Buffer rate of 5-DOL
61 894 737	5-DOL to treatment/day
6	hatchling ret. time (days)
0,70	Hatching rate of eggs
88 421 053	eggs/day
4	Egg retention time (days)
250	eggs/Fly
353684	Flies/day
5	Fly retention time (days)
0,80	Emerging rate of pupae
442105	Prepupae/day
20	Prepupa ret. time (days)
0,75	Transformation rate of larvae
589474	5-DOL to nursery/day
18	Larva retention time (days)
0	Buffer days for all carriers
0,30	Used spae building
0,30	Used space nursery

Figure 39: parameters entered in Eawag's computational costing tool for BSF infrastructures

The basic process follows five steps. First, adult BSF are reared in cages where they mate and lay eggs on cardboard or wooden strips placed near a moist attractant. These eggs are collected and incubated until they hatch, producing small larvae. After five days, the so-called 5-day-old larvae (5-DOL) are ready to be used as the "seed stock". In the treatment unit, the 5-DOL are placed in shallow basins (larveros), where they receive waste feed three times during the 12-day cycle (on day 1, day 5, and day 8). The waste is spread in layers no thicker than 5 cm to avoid overheating. As they develop, the larvae reduce the waste mass significantly. At the end of the cycle, larvae tend to crawl out of the substrate, to darker place for their metamorphose, and they can be collected using sieves or by encouraging them to crawl into collection containers. The residue (frass) is separated at the same stage and sent for further stabilisation.
Dortmans et al. (2017) proposes 100 m^2 treatment surface per ton of daily waste input, implying around 6,500–7,000 m^2 for Essaouira. With multi-tier shallow basins or pallet bins (6 tiers), this translates to approximately 3,000 m^2 floor space. Pre-processing would remain simple: hand-picking, a belt magnet, and shredding to <10–15 mm.

The most critical challenge at this scale is the colony management unit. To inoculate 63.6 t/d, approximately 62 million 5-day-old larvae (5-DOL) are required per day. Maintaining such a colony demands robust egg

production, protection against parasites (e.g. *Dirhinus giffardii*), and controlled temperature/humidity in adult cages. Studies from industrial farms show that poor management of the rearing unit can drastically reduce emergence and egg output, creating a bottleneck.
Labour intensity is also significant. Zurbrügg et al. (2018) suggests around 6 workers per ton at 1 t/d scale, but economies of scale reduce this to ∼0.6 workers per ton at 60 t/d. The Eawag model estimates around 50 full-time workers and 2 managers, with a concentration in pre-processing, feeding, harvesting, and colony management.
BSF composting for Essaouira is technically feasible and offers the dual benefit of waste reduction and valuable products (larvae meal, oil, and frass). However, at 65 t/d scale it faces substantial operational complexity, especially in maintaining a reliable colony output and managing labour.

6.1.4 Economic Feasibility

Mechanical Sorting:
The capital cost of an MBT facility is highly dependent on plant scale, scope, and technology level. In Morocco, two recent CEV/MBT provide useful benchmarks. The CEV of Marrakech was constructed for an estimated 131 million MAD to treat approximately 330,000 t/yr of waste, of which around 30 million MAD was attributed specifically to the mechanical separation section (Morocco's Environment Ministry, 2019). In Meknès, the CEV investment was reported at 240 million MAD for a facility designed to handle roughly 200,000 t/yr (Suez, 2016). Scaling these figures to Essaouira's projected 40,000 t/yr capacity highlights the effect of economies of scale. Using a six-tenths scaling rule (exponent 0.65), the Marrakech separation line translates to roughly 7–10 million MAD in process equipment costs at Essaouira's scale. When adding buildings, civil works, interconnections, and installation, the total installed cost of the mechanical treatment section is expected to reach 20-25 million MAD. This estimate reflects the leaner configuration designed for Essaouira (manual bag opening, manual sorting line, a single wind-sifter, and one RDF shredder+baler), which avoids some of the more capital-intensive machinery typically found in larger CEVs.
Operating costs for mechanical treatment lines are typically benchmarked as a fraction of the initial investment. International references indicate that annual OPEX usually ranges between 20–35% of CAPEX, depending on the level of automation, labour intensity, and maintenance requirements. For Essaouira's configuration, where manual bag opening and a manual sorting line are retained to reduce equipment complexity, operating costs can be expected in the upper tranche of this band. This corresponds to approximately 6–8 million MAD per year (≈155–195 MAD/t).

In terms of revenues generated per year, these include the sale of reyclables separated during the sorting process, as well as the sale of the RDF fraction. Based on the material flows in figure 36, the mechanical separation line of the MBT in Essaouira would recover about 1,168 t/y of plastics, 277 t/y of cardboard, and 365 t/y of metals, alongside a lightweight RDF fraction of 6,341 t/y. Information on the prices of these recyclables were displayed in Table 15. However, these prices came from informal waste pickers, who can obtain high prices because of the high quality of their recyclables. The output from MBT facilities is typically more contaminated and therefore trades at lower values. Applying a conservative 60% of the informal market prices, plastics can be valued at roughly 2,100 MAD/t, cardboard at 420 MAD/t, and metals at 1,500 MAD/t, while RDF is assumed to sell at around 35 EUR/t (380 MAD/t) (Ouigmane et al., 2022). This yields annual revenues of about 2.45 M MAD from plastics, 0.12 M MAD from cardboard, 0.55 M MAD from metals, and 2.41 M MAD from RDF. In total, the mechanical separation could therefore generate in the order of 5.5 M MAD per year (∼0.5 MEUR), with plastics and RDF providing the bulk of the income.

Biological Treatment:
As for the biological treatment of the OFMSW, actual costs for AD plants are more difficult to find and estimate. European reference tables (Waste Control, n.d.) list **dry AD** processing around 25 kt/y at 8–9 M (≈320–360 EUR/tpa), while other AD plants are in the 250–600 EUR/ tpa band depending on spec and scale. Applying those EUR/tpa anchors to 22 kt/y gives a 5–9 M CAPEX range for the AD process (pre-treatment for OFMSW, digesters, gas handling/CHP, basic odor control, digestate handling). Typical OPEX in these tables is 26–60 EUR/t treated, or around 730 000 EUR/y in the lower range. Other information online give price ranges around 400 000 EUR–5 M for an entire plant, depending on the size and scope (Last, 2022).

For **wet AD**, reference data show 50–60 kt/y AD lines slightly more expensive at 270–583 EUR/tpa (i.e., 13.5–35 M at that size), and 120 kt/y wet AD at 167–250 EUR/tpa; a 70 kt/y wet AD example is reported at 11.5 M (165 EUR/tpa). For 22 kt/y, a cautious scaling of the EUR/tpa bands yields 7–11 M CAPEX for a wet AD block with standard MSW pre-treatment (degritting/deplastifying), CHP, and odor control. OPEX in the same sources sits broadly in the 30–60 EUR/t bracket, or around 850 000 EUR/y.

In the case of Morocco, where slightly lower costs could be expected due to lower wages and installation costs, the price for Essaouira's AD could be situated in the lower range of the previous prices. We could therefore assume around 4M for a dry AD and 7M for a wet AD process. The revenues from AD are generated through the sale of electricity and heat from the CHP unit, and from potential sale of fertilizer. At Essaouira's scale, with the electricity price at around 0.1EUR and the heat price half of that, this corresponds to an annual revenue of about 1.37–1.42 million EUR for wet AD (electricity, heat, and 13,870 t/y of digestate), and around 1.13–1.17 million EUR for dry AD (electricity, heat, and 9,892 t/y of digestate).

Investment and operating costs for **BSF composting** differ substantially from anaerobic digestion, as the process relies more on labour, rearing infrastructure, and handling surfaces than on heavy process equipment. Using the Eawag BSF costing tool (Eawag, 2017), scaled to Essaouira's 63 t/d OFMSW input, the indicative costs are easily computed.
CAPEX are at approximately 1.33 million EUR(≈14.5 million MAD), covering treatment building equipment (shredders, conversion crates, dryers, oil presses, pelletisers), the reproduction unit (nursery cages, egg media, pupation crates), and basic civil works. OPEX are around 650,000 EUR per year (7.1 million MAD), largely driven by labour (50 workers and 2 managers), together with electricity, water, and minor consumables.
The model also estimates daily and annual outputs and revenues:

- Live larvae: ∼15.8 t/d (≈5,749 t/y), sold at 0.20 EUR/kg → 1.15 million EUR/y.
- BSF meal: ∼2.8 t/d (≈1,035 t/y), sold at 1 EUR/kg → 1.035 million EUR/y.
- Compost (frass): ∼12.6 t/d (≈4,599 t/y), sold at 0.05 EUR/kg → 0.23 million EUR/y.

This results in potential gross annual revenues of around 2.4 million EUR. Even after accounting for the 0.65 million EUR annual OPEX, the operation could theoretically yield a positive gross margin, provided that markets for larvae protein and meal are secured.

Summary:
Table 19 provides an overview of the indicative investment and operating costs, as well as the potential annual revenues, for the treatment components considered in Essaouira's MBT concept. The figures highlight the contrast between the higher CAPEX but relatively stable revenues of anaerobic digestion, the labour-intensive but lower-CAPEX profile of BSF composting, and the intermediate position of mechanical sorting, where revenues depend strongly on market conditions for recyclables and RDF.

Table 19: Indicative CAPEX, OPEX, and annual revenues for MBT components in Essaouira

Treatment option	**CAPEX**	**OPEX (annual)**	**Revenues (annual)**
Mechanical sorting	20–25 M MAD	6–8 M MAD	∼5.5 M MAD (∼0.5 MEUR)
Dry AD (22 kt/y)	∼4 MEUR (44 M MAD)	∼0.73 MEUR (8 M MAD)	1.13–1.17 MEUR (12–13 M MAD)
Wet AD (22 kt/y)	∼7 MEUR (77 M MAD)	∼0.85 MEUR (9 M MAD)	1.37–1.42 MEUR (15 M MAD)
BSF composting (63 t/d)	1.33 MEUR (14.5 M MAD)	0.65 MEUR (7.1 M MAD)	∼2.4 MEUR (26 M MAD)

6.1.5 Environmental and social impact

Environmental outcomes
At the assumed 40,000 t/y input, the MBT configuration in Figure 36 yields the following annual material outcomes:

- **Organics sent to biological treatment:** ∼24,400 t/y (≈61%).
- **RDF (lightweight combustible fraction):** ∼6,340 t/y (≈16%).
- **Recyclables (from manual sorting + metal removal):** ∼1,168 t/y plastics, ∼277 t/y cardboard/-paper, and ∼365 t/y metals (≈4.5–5% combined).
- **Residual inerts (ultrafines + wind-sifter heavies):** ∼7,400 t/y (≈18.5%) to landfill.

Diverting the organic fraction from landfill avoids leachate generation, soil contamination, but also methane generation under uncontrolled anaerobic conditions. Using conservative IPCC default factors for mixed MSW[1] gives an avoided methane of:

$$24{,}400\text{t/y} \times 0.04 \frac{\text{t CH}_4}{\text{t}} \approx 980\mathbf{t}\ \mathbf{CH}_4/\text{y}$$

Using a 100-year global warming potential for CH_4 of 27.2, this corresponds to:

$$\approx 26{,}700\text{t CO}_2\text{e/y}$$

Additional benefits accrue from (i) **RDF** displacing fossil fuels in cement kilns (subject to kiln spec compliance) and (ii) **recycling** plastics/cardboard/metals, which avoids upstream extraction and manufacturing impacts. If the organic fraction is stabilized via AD, on-site energy recovery further offsets emissions:

- **Wet AD (base case):** ~12.2–13.6 MWh_{el}/d ⇒ ~4.5–5.0 GWh_{el}/y, with a similar magnitude of useful heat (11–14 MWh_{th}/d).
- **Dry AD:** ~11.2–12.5 MWh_{el}/d ⇒ ~4.1–4.6 GWh_{el}/y, with ~11–14 MWh_{th}/d heat.

Expressed as household-equivalents (assuming 1,500 kWh/household·year), the exported electricity could supply roughly **2,900–3,300 households**. Heat can cover digester and building demands with surplus for low-grade uses (e.g., digestate/RDF drying).

Social outcomes
The MBT concept is designed to **integrate the informal recycling community** into safe, formal jobs:

- **Inclusive manual sorting line:** Target 6-8 pickers on the line (3 per side) plus a line lead and baler operator per shift (with rotation and breaks ⇒ ~10–12 rostered staff/shift), prioritizing experienced informal pickers. Provide formal contracts, fair wages, PPE (gloves, masks, safety shoes), vaccinations, and H&S training.
- **Broader employment:** Mechanical section (reception, loaders, maintenance), **AD** (operators, electromechanical, lab/QA), or **BSF** (colony management, feeding/harvesting, processing) together support on the order of **30–70 full-time jobs** depending on the chosen biological route (BSF at the higher end due to labour intensity).
- **Skills and formalization:** On-the-job upskilling (quality control for recyclables, equipment safety, basic lab skills), pathways for women and youth, and recognition of prior informal expertise.
- **Local value chains:** Stable **offtake partnerships** with cement kilns (RDF), local scrap/plastic buyers (recyclables), farmers/land reclamation (digestate/compost-like output), and—if BSF is pursued—feed mills/poultry producers (larvae meal and oil).

Together, these measures improve livelihoods and safety for current waste pickers, while raising material recovery, sanitation, and environmental performance at city scale.

[1] Assumptions: degradable organic carbon DOC = 0.15 t,C/t; fraction of DOC that degrades $DOC_f = 0.5$; methane correction factor MCF = 0.8 for unmanaged conditions; methane fraction $F = 0.5$; stoichiometric factor 16/12 to convert C to CH_4. This yields ~0.04 t,CH_4/t waste.

6.2 Landfill Leachate Treatment

The treatment of the landfill's leachate is very complicated in Morocco in general. In the case of Essaouira, Section 2.3.2 showed that the leachate was characterized by a very high COD and a low BOD leading to a very low BOD/COD ratio of 0.06, indicating that only 6% of the organic matter is readily biodegradable, and the rest is composed of recalcitrant organics. This low ratio shows poor biodegradability, a key challenge for biological treatment. The leachate also has high mineral content, heavy metals contamination (especially chromium), and alkaline pH of 8.4. Moreover, it likely contains high ammonia-N (common in mature leachates, though not explicitly noted by Chiguer et al., 2016). This leachate has typical characteristics of very old leachate, resembling to an abandoned site. Table 20 shows the leachate quality and concentrations of different contaminants.

Table 20: Composition of Essaouira Landfill Leachate (data from Chiguer et al., 2016)

Parameter	**Observed Range**	**Mean Value**
COD (mg/L)	6,106 – 13,939	10,361
BOD_5 (mg/L)	207 – 851	632
BOD_5/COD ratio	0.03 – 0.08	0.06
Electrical Conductivity (μS/cm)	–	39,983
Chromium (total Cr, μg/L)	–	~1,720
Lead (Pb, μg/L)	–	<1,000 (Meets standard)
Cadmium (Cd, μg/L)	–	<200 (Meets standard)

Currently, the Essaouira landfill uses only passive treatment. However, long-term storage in ponds has not significantly reduced the pollutant load, and the leachate remains "significant and almost stable over time" despite prolonged retention, according to Chiguer et al. (2016). Clearly, more robust treatment steps are required to achieve safe discharge quality. The goal of this section is to propose a method to treat this leachate for safe environmental discharge (meeting Moroccan norms for COD, BOD_5, metals, etc.). Given the leachate's composition, a multi-step treatment train is proposed, combining physical/chemical and biological processes in a targeted sequence. Each stage will address specific pollutant categories, matching pollutant types to appropriate removal technologies. The recommended treatment chain is derived from course material on landfill leachate treatment (Professor Jules Van Lier, 2023) and is illustrated in Figure 40.

It is important to note that, due to the low BOD/COD ratio, biological treatment alone is not feasible as a first-line treatment, since the biodegradable fraction is too small. Instead, the treatment chain will focus on physico-chemical treatments and oxidation up front, to reduce pollutants and improve biodegradability. Biological treatment can then be applied as a polishing step if needed when the remaining organics are more amenable to biodegradation.

1. Preliminary Conditioning (Equalization & pH Adjustment): First, the raw leachate should be collected in an equalization basin to homogenize its composition and flow, as is currently done. This buffers any fluctuations in pH or concentration, since leachate quality can vary seasonally or with rain events. Given that the leachate is alkaline (pH 8.4), we should adjust it downward in preparation for Step 2. Only a small amount of acid (such as H_2SO_4) should be added here, since the main pH adjustment is integrated into the next step.

2. Acidic Coagulation–Flocculation (Humic COD Removal): The goal of this step is to remove recalcitrant organics (mainly humic and fulvic acids) which contribute significantly to the COD and dark color of mature leachate. These compounds are poorly biodegradable and can bind heavy metals later in the process. By removing them early, we reduce the COD load and avoid contaminating them with metals, allowing for safer and potentially beneficial reuse.
To achieve this, the equalized leachate is acidified to pH 2–3 using a strong acid (e.g. sulfuric acid like in step 1), which protonates the functional groups of humic acids, causing them to lose solubility and aggregate (Costa et al., 2025). A small dose coagulant such as ferric chloride or aluminum sulfate can also be added at low pH to enhance floc formation, and polymer flocculants may be used to strengthen it further.
Solid-liquid separation should follow to recover the flocs. Dissolved Air Flotation (DAF) is generally preferred due to the low density of humic flocs. However, clarifiers or sand filters may also be used. This step can remove up to 80–90% of COD and color (Costa et al., 2025). Crucially, heavy metals remain largely dissolved at low pH, so the humic-rich sludge contains minimal contamination.
The separated organics can be dewatered (e.g. drying beds, filter press) and stabilized. If confirmed low in metals, the material may be reused as a soil amendment. Even if not reused, its disposal is easier and safer than metal-contaminated sludge. Overall, this step reduces COD early and isolates relatively clean organics for separate handling.

3. Alkaline Precipitation (Heavy Metal Removal): After humic acid removal, the leachate still contains dissolved heavy metals (e.g., Cr, Pb, Cd, Ni, Zn) and some suspended solids. To remove these, the pH should be raised to 9.5–10.5 using lime ($Ca(OH)_2$) or NaOH. At this high pH, metals precipitate as hydroxides (e.g., $Cr(OH)_3$, $Zn(OH)_2$) or carbonates. Chromium, in particular, is efficiently removed as Cr(III) hydroxide, especially if any toxic Cr_6 was previously reduced to Cr^{6+}. A reducing agent like ferrous sulfate can be added to do so.
It is worth noting that, in old mature leachates, sulfide (HS^-) is often present and can further improve metal removal by forming insoluble sulfide precipitates (e.g., PbS, CdS, ZnS) (Kjeldsen et al., 2002). If needed, supplemental sulfide (e.g., Na_2S) may be added. However, chromium is the exception, as it does not form sulfide precipitates and must be removed as hydroxide (Kjeldsen et al., 2002).
This step benefits from the prior removal of humics, which avoids metal-organic complexation and saves reagents.Coagulants like ferric chloride ($FeCl_3$) may be added to improve flocculation and co-precipitate trace metals and phosphates. The mixture should then be stirred and flocculated before being clarified. The resulting sludge should contain heavy metal hydroxides, sulfides, and excess lime solids.
Because of its metal content, this sludge is hazardous and must be disposed of in a secure landfill cell or stabilized with cement. The treatment is highly effective, achieving 80–95% removal of metals like Cr, Pb, and Cd (Meka et al., 2013). For example, Cr can be reduced from 1–2mg/L to below 0.2mg/L, meeting Moroccan standards. Phosphate and carbonate hardness are also removed in this step, and the final pH ($\approx$10) is optimal for the next process: ammonia stripping.

4. Ammonia Stripping (Nitrogen Removal): Following metal removal, the leachate still contains high concentrations of ammonia (often hundreds to thousands of mg/L), which is toxic and must be reduced to meet discharge standards (e.g., total nitrogen <10mg/L in Morocco, Idlahcen et al. (2021)). Since the leachate is already at high pH (10–10.5), ammonia exists primarily in its volatile form (NH_3) due to the equilibrium according to the equilibrium $NH_4^+ + OH^- \leftrightarrow NH_3 + H_2O$, and can be removed via air stripping (Guo et al., 2010).
Here, the leachate flows through a packed stripping tower where air is blown for up to 18 hours countercurrently, volatilizing NH_3. The gas is captured in an acid scrubber using sulfuric acid, forming ammonium sulfate ($(NH_4)_2SO_4$).
This method typically removes 70–90% or more of ammonia (Dos Santos et al., 2020; Guo et al., 2010; Moujanni et al., 2019), reducing subsequent oxygen and oxidant demand. It is favored over biological nitrification-denitrification, which also remove nitrogen, due to the leachate's low BOD (prevents growth of denitrifying bacteria), high salinity, and potential metal inhibition.
Air stripping units are considered simple, low-energy systems widely used in wastewater treatment. Therefore, ammonia stripping is selected for Essaouira due to its robustness, simplicity, and strong local feasibility. This process also produces a usable byproduct: ammonium sulfate solution, which can be used as common fertilizer if pure enough. If reuse as fertilizer is not viable due to impurities, the ammonium sulfate solution can be evaporated in solar ponds alongside RO brine. As an alternative, recent research (Mutahi et al., 2024) suggests using organic acid scrubbers (e.g., citric acid) paired with Bipolar Membrane Electrodialysis (BPMED) to recover ammonia and regenerate the acid, offering a more sustainable but complex option for future consideration.
Overall, this step substantially reduces ammonia and also removes some carbonate hardness and magnesium. The effluent remains alkaline (pH 10) and will be acidified in the next step for Fenton oxidation. Any residual ammonia will be polished biologically later. At this point, most inorganic contaminants are removed, and attention shifts to degrading persistent organic compounds.

5. Advanced Oxidation Process (Organic COD Removal): This step targets persistent organics (e.g. fulvic acids, phenols) that remain after upstream treatment. The goal is to reduce COD below discharge standards (500 mg/L) and improve biodegradability (higher BOD_5/COD ratio) ahead of biological polishing. However, it is important to note that this step may not be strictly necessary.
According to expert advice from Prof. van Lier, much of the remaining COD after upstream steps is made up of humic-like substances, which are not toxic or readily biodegradable, and not regulated individually. Removing these stable compounds using Advanced Oxidation Process (AOP) can be quite costly and chemically intensive, with limited environmental benefit. In some cases, it may be more economical and equally safe to tolerate higher residual COD, especially if the effluent is not discharged into sensitive water bodies. Moreover, later steps will further remove some COD.
However, some AOP is still proposed here in the case it is deemed necessary by the people in charge. AOPs such as UV/H_2O_2 and ozonation are technically capable of degrading non-biodegradable organic compounds, but they are not suitable for Essaouira due to their high operational costs, sensitivity to leachate salinity and turbidity, and the need for advanced process control. The leachate's very high conductivity and poor UV transmittance would significantly reduce AOP efficiency, making them impractical under local budget and technical constraints. Therefore, Fenton's reagent (Xiang et al., 2025)—an iron-catalyzed hydrogen peroxide

treatment— could be selected as the most suitable AOP for Essaouira. It uses ferrous iron (Fe^{2+}) and hydrogen peroxide (H_2O_2) at acidic pH (2.5–3) to generate hydroxyl radicals (•OH), which aggressively oxidize complex organics.
Although the leachate exits the ammonia stripper at pH ≈10, prior humic acid removal reduced its buffer capacity, making acidification more manageable. The pH is lowered using sulfuric acid, and Fe^{2+} (typically from $FeSO_4$) is added, followed by gradual H_2O_2 dosing. The process is run for 1–2 hours under stirring, after which the pH is raised to 7–8. This neutralization precipitates ferric hydroxide ($Fe(OH)_3$), which also helps coagulate and remove oxidized organic fragments. The resulting sludge is then settled or filtered out.
Fenton can reduce COD by up to 60-70% (Guo et al., 2010; Xiang et al., 2025), uses simple and locally available reagents (iron salts and H_2O_2), and only requires basic batch reactors. However, conventional Fenton faces drawbacks: sludge production ($0.8\text{–}1.2 kg/m^3$), strict pH control, and non-recoverable iron catalysts (Guo et al., 2010; Xiang et al., 2025). To address these, research have developed a Fe-GAC-based heterogeneous Fenton system achieving up to 94% COD removal. Moreover, Fenton also offers the benefit of destroying organic micro-pollutants (Németh et al., 2019). For these reasons, Fenton's reagent is a highly practical and effective choice for tackling the persistent COD load in Essaouira's leachate.

6. Biological Polishing (Aerobic Treatment): After the potential Fenton oxidation, the leachate should contain significantly reduced COD and a higher proportion of biodegradable compounds. At this stage, we can introduce biological treatment to polish the effluent, targeting residual BOD, remaining COD, and any leftover ammonia.
A small-scale aerobic system is appropriate for Essaouira's modest leachate flow (≈8 m^3/day, Chiguer et al., 2016). Sequencing Batch Reactor (SBR) is therefore excluded. Options include an activated sludge reactor, Moving Bed Biofilm Reactor (MBBR), or aerated lagoon. Given Morocco's warm climate low financial resources, a simple aerated lagoon or a series of stabilization ponds is practical and low-cost. These systems can effectively degrade residual organics and nitrify any ammonia that escaped stripping, converting it to nitrate. If nitrate removal is needed, an optional anoxic zone could enable denitrification, though this is less pressing under Moroccan standards.
This biological step is chosen for its affordability, simplicity, and alignment with nature-based treatment preferences. By the time the leachate reaches this stage, upstream processes will have removed inhibitory substances, making biological treatment viable and efficient. Overall, this step serves as a reliable and cost-effective safeguard to ensure compliance with COD and BOD discharge standards while promoting sustainable treatment practices.

7. Tertiary Treatment – Membrane Filtration through Ultrafiltration and Reverse Osmosis (Desalination): The final challenge is the high salt concentration in the leachate, with electrical conductivity reaching ≈40 µS/cm. These dissolved salts (chloride, sodium, sulfate, etc.) remain even after metals and organics are removed. To avoid harming soil and water systems through salinity stress, a membrane filtration is proposed, specifically Ultrafiltration (UF) and Reverse Osmosis (RO).
UF first removes fine solids, colloids, and microbes. It has to be implemented before RO in order to protect the RO membranes from fouling. It acts a as a barrier to any biomass from upstream biological steps. A cartridge filter should follow UF to catch any residual particles and prevent membrane damage.
Afterwards, RO forces water through semipermeable membranes, rejecting salts and residual organics. With 95–99% salt rejection efficiency, RO produces a low-conductivity permeate and a concentrated brine requiring dedicated management. The simplest and most viable brine disposal method is solar evaporation (lined basins where Morocco's high sun exposure accelerates evaporation). Solid residues can be collected and landfilled. This avoids costly liquid-discharge systems while still handling the concentrate safely. RO units, especially containerized systems, are commercially available and increasingly used in the region, with the Oum Azza landfill near Rabat having explored RO (Elfilali et al., 2021).

Conclusion:
The complex composition of Essaouira's leachate, marked by high salinity, refractory organics, heavy metals, and ammonia, requires a robust, multi-barrier treatment approach. The proposed train illustrated in Figure 40 integrates cost-effective physico-chemical steps with targeted oxidation and biological polishing, culminating in reverse osmosis for final desalination. Each stage is tailored to local constraints and pollutant characteristics, ensuring both technical feasibility and environmental compliance. Implementing this sequence would significantly enhance leachate quality and support safer, more sustainable landfill operations in Essaouira.

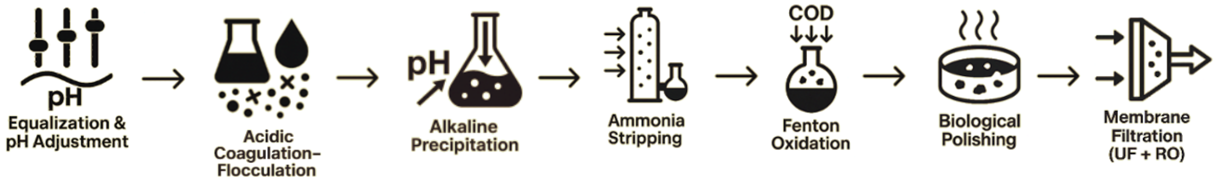


Figure 40: Lechate treatment chain proposed for Essaouira's landfill

6.3 Landfill Gas Management After Closure

Following the strategic recommendations, two alternative technical approaches are considered for controlling lLFG emissions after the closure of the Essaouira site: (1) active gas well systems and (2) methane oxidation layers (MOL). Both aim to reduce methane emissions but differ significantly in complexity, efficiency, and cost.

But first, we must estimate methane emissions from the Essaouira landfill. to do so, historical waste input data were first reconstructed. Figure 3 presented official records of annual tonnages disposed between 2001 and 2014, showing an increase from about 14,700 t/y in 2001 to around 26,000–28,000 t/y by 2014. Current records indicate that waste inputs have continued to rise, reaching approximately 40,000 t/y in 2025. On this basis, yearly tonnages between 2001 and the present were estimated, thereby providing a continuous input series for modelling purposes. For simplicity, the waste composition was assumed to have remained constant throughout this period.
With these data, the Afvalzorg Landfill Gas Model (NV Afvalzorg Holding, 2025) was applied to estimate methane generation both retrospectively (2001–2025) and prospectively (2026 onwards). The model follows the IPCC (2006) First-Order Decay (FOD) approach, widely used for greenhouse gas inventories, which calculates methane production as a function of waste inputs, climate, and landfill conditions.
The following assumptions were used in the model for the Essaouira case:

- The landfill began operation in 2001 with 14,700 t of MSW disposed, increasing steadily to about 40,000 t/y in 2025, with constant waste composition over time.
- Waste composition is rich in biodegradable organic matter, represented by a Degradable Organic Carbon (DOC) value of 0.17 and a DOC_f (fraction that degrades) of 0.63, following IPCC guidelines for mixed MSW in low-income contexts.
- Given the absence of engineered design, compaction, or cover systems, and the depth of the waste mounts, a Methane Correction Factor (MCF) of 0.7 was applied.
- No methane oxidation system is currently in place; thus, the oxidation factor (OX) was set to 0, meaning that all methane generated is assumed to be emitted unless captured.
- A dry, warm climate justifies a decay rate constant (k) of 0.065 yr^{-1}, consistent with IPCC defaults for dry tropical conditions.

The resulting model outputs provide estimates of methane generation over the landfill's operational and aftercare phases, allowing both the cumulative emissions to date and the remaining potential emissions to be assessed. These outputs form the basis for evaluating closure and gas management strategies presented in this section.

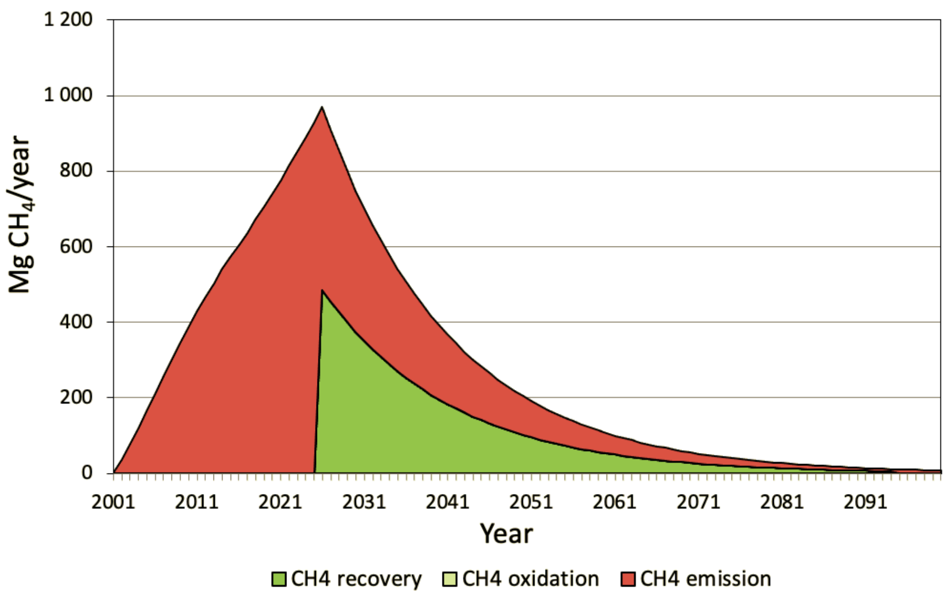


Figure 41: Estimated cumulative methane emissions in Essaouira landfill (2001-2025) (NV Afvalzorg Holding, 2025)

Figure 41shows that, to date (2001–2025), the Essaouira landfill is estimated to have generated around 12,000 tons CH_4, of which essentially all has been emitted to the atmosphere due to the absence of any compaction, capture, or oxidation systems. If the landfill were to be closed in 2025, the remaining methane generation potential is still substantial: the Afvalzorg model projects approximately 6,600 tons CH_4 to be released over the following three decades. This corresponds to a climate impact of around 185,000 t CO_2-eq (using GWP100 = 28).

6.3.1 Option 1 — Active Gas Well System

Active landfill gas collection systems typically consist of a network of vertical extraction wells drilled into the waste body, connected via horizontal header pipes to a central blower and treatment unit. For closed landfills such as Essaouira, wells are installed by drilling through the final cover and inserting perforated high-density polyethylene (HDPE) pipes into the waste mass, usually to a depth of two-thirds of the waste thickness. The annulus around the well is backfilled with coarse gravel to facilitate gas flow, and the top is sealed with bentonite or clay to prevent air intrusion. A grid spacing of 30–50 m between wells is common, though this must be adapted to site-specific waste depth and permeability.
The individual wells are linked by a network of lateral and main header pipes that convey the gas under negative pressure, generated by a blower. At the treatment station, the gas can either be flared in a high-temperature flare or used in a combined heat and power (CHP) unit to generate electricity and heat. A condensate management system (traps and sumps) is required along the piping to remove moisture from the gas stream. Routine monitoring of flow rates, methane content, and wellfield pressure ensures stable operation and prevents air ingress, which can otherwise lead to subsurface fires.

Installing an active gas well system from 2026 onwards would allow for the recovery of a significant share of this methane. Assuming a typical operational capture efficiency of 50% sustained over a 30-year control period (2026–2056), roughly 3,300 tons CH_4 (92,500 t CO_2-eq) could be prevented from being emitted to the atmosphere, which which corresponds to approximately 4.61×10^6 m^3 CH_4 at STP (3,300 Mg CH_4 / 0.716 $kg\,m^{-3}$). Assuming CHP yields of around 3kWh_{el} per m^3 CH_4, the captured gas would generate about **13.83 GWh_{el}** over 2026–2056—i.e., roughly 300 households per year at 1,500 $kWh\,hh^{-1}\,y^{-1}$.

The costs of implementing such a system can be benchmarked against literature estimates. Damgaard et al. (2011) report installation and operational costs for active landfill gas systems in the range of 1–3 EUR per ton of waste disposed, which in Essaouira's case (≈ 690,000 t of waste cumulatively landfilled by 2025) would correspond to **0.7–2 M EUR**. These costs could be at least partially offset by revenues from energy recovery. If the estimated 13.83 GWh of electricity were sold at a market value of 0.1 EUR/kWh, this would generate approximately 1.4 M EUR, covering a significant share—and potentially the entirety—of the implementation costs.
Additionally to the revenues of electricity sale, some money could be generated through the sale of carbon credits. These represent a promising avenue for financing landfill gas projects, especially in regions like Morocco where such systems are not yet mandatory, since in order to be eligible for carbon credit certification, a project must meet the principle of additionality. In voluntary or Clean Development Mechanism (CDM) markets, each verified ton of CO_2-equivalent emission reduction—such as through methane capture and flaring—can be converted into a tradable carbon credit. In general, one credit equals one ton of CO_2 (or equivalent gases) reduced or avoided, and can be sold to private actors or governments aiming to offset their emissions.
However, verification plays a critical role and can be quite complicated, as credits can only be issued after validation by an approved third party that ensures emission reductions are real, measurable, and permanent.
In principle, the 3,300 tons of methane (or 92,500 tons CO_2) potentially avoided through gas well system could be sold as carbon credits. The current price of 1 ton of CO_{2eq} in Europe is around 60 EUR (Sandbag, 2025). However, this price varies depending on the location and type of project it comes from. Therefore, for a landfilling project in Morocco, the price of 1 ton of carbon dioxide can be expected to decrease to around 10 to 30 EUR, bringing to a total of **0.92-2.78 M EUR** generated.

Overall, installing an active gas well system would represent a technically mature and cost-effective option for mitigating post-closure emissions at Essaouira landfill. It combines significant GHG reduction potential with the opportunity to generate renewable electricity, though the economic feasibility depends strongly on the ability to market the recovered energy and/or secure carbon finance.

6.3.2 Option 2 — Methane Oxidation Layer (MOL)

An alternative or complementary system to active gas extraction is the installation of a MOL, also referred to as a biocover (see Figure 42). The principle is to exploit naturally occurring methanotrophic bacteria in soils or compost-amended covers that oxidize CH_4 into CO_2 as the gas diffuses through the cover system. This approach transforms a potent greenhouse gas into one with a much lower global warming potential, without the need for mechanical capture or energy conversion equipment.

The oxidation efficiency of MOLs varies widely. Laboratory and field studies report potential CH_4 conversion fractions ranging from below 10% to above 50%, depending on methane flux, soil porosity, moisture, and temperature conditions. The IPCC (2006) therefore recommends a conservative default value of 10% oxidation for inventory purposes, while engineered covers enriched with compost or biochar have occasionally reached 30–50% under favorable conditions (Professor Julia Gebert, 2024). However, efficiencies tend to decline at high methane fluxes, where oxygen becomes limiting and preferential flow channels bypass the oxidation zone.

Compared to active gas well systems, MOLs are less capital-intensive, as they mainly require construction of an amended soil or compost cover (typically 0.5–1.0 m thick) and ongoing maintenance. Exact costs are highly site-specific, but they are generally lower than the 1–3 EUR/t waste reported for active systems. The trade-off is lower and more uncertain performance, especially under dry climates where microbial activity may be moisture-limited. Moreover, no revenues can be generated through the capture of CO_2 or the sale of carbon credits, since it is complicated to actually measure and demonstrate the amount of methane captured.

For the Essaouira landfill, a MOL could in principle provide a passive and relatively low-cost mitigation measure after closure, but it should be complementary to the gas well system, as its actual efficiency is highly uncertain. The site is characterized by dry, windy conditions that could limit soil moisture and microbial activity. Furthermore, the effectiveness of a MOL depends on subsurface conditions such as waste compaction, settlement patterns, and the presence of cracks, root channels, or other preferential pathways that could allow methane to escape without passing through the oxidation layer. Without detailed investigations into the current state of the landfill body and its cover system, it is not possible to reliably estimate achievable oxidation percentages.

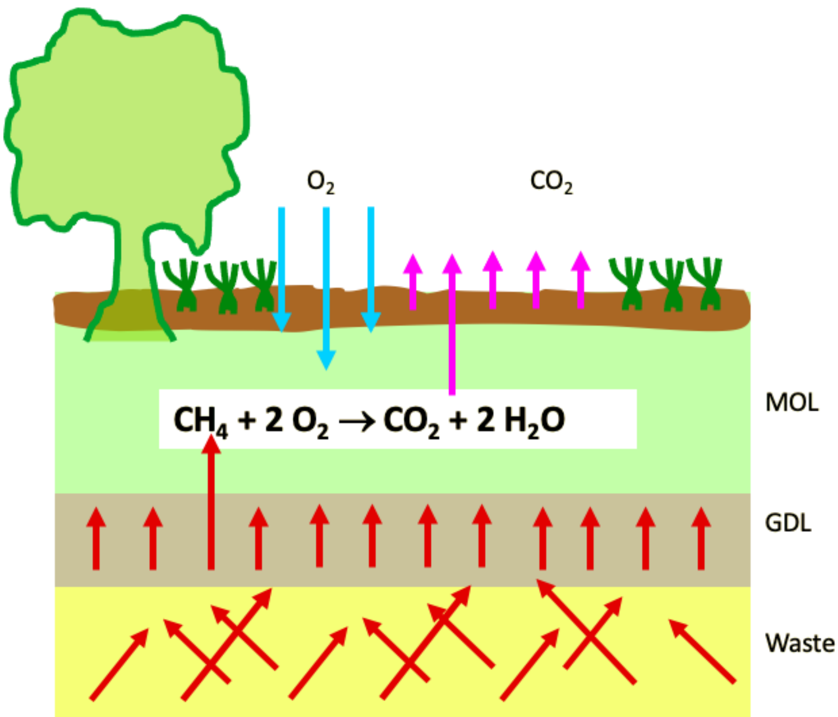


Figure 42: MOL design for a landfill capping (Professor Julia Gebert, 2024)

7 Answering Main RQ

This section will try to answer the two remaining subquestions:

4. **What are the best practices of MSWM in developed countries ?**

5. **What improvements can be implemented to enhance waste management in Essaouira?**

The literature review in Section 2.6 answered subquestion 4 by examining MSWM systems in high-performing developed countries such as Belgium, Germany, the Netherlands, Sweden, and Denmark. While these countries differ in governance structures and local constraints, common best practices emerged. These include the implementation of crucial source separation systems for organics and recyclables, advanced recycling and composting infrastructure, and waste-to-energy recovery for residuals. Also, the widespread deployment of MBT plants has proven effective in reducing the organic fraction of residual waste prior to landfilling or incineration, thereby lowering methane emissions and enhancing material recovery. In parallel, the establishment of sanitary landfills designed with leachate collection and gas management systems has been a cornerstone of European practice, ensuring that the fraction of waste which cannot be further valorized is disposed of in a controlled and environmentally sound manner. Together, MBT and sanitary landfilling have provided a reliable safety net in Europe's integrated waste hierarchy, complementing recycling and energy recovery while minimizing environmental risks. In terms of public engagement strategies, they include education campaigns and incentive-based schemes like Pay-As-You-Throw (PAYT) and Deposit-Refund Systems (DRS). Importantly, these strategies are supported by strong institutional coordination, transparent performance monitoring, and inclusive policies that recognize the role of informal workers. While Essaouira differs significantly in socioeconomic context, some practices were identified as critical to its profile, especially those focused on source separation, centralized recovery systems, landfill sanitation, and citizen participation.

Then, chapter 5 (Strategic Recommendations) and 6 (Practical Engineering Recommendations) addressed the final subquestion, thereby helping answering the main Research Question:
How to improve Essaouira's MSWM system ?

7.1 Strategic Recommendations

This sections sets the strategic priorities that guide Essaouira's MSWM transition, flagging quick, low-cost service fixes, establishing source separation as the system's backbone, and framing treatment/landfill actions that the subsequent engineering chapter translates into concrete designs.

Collection & public cleanliness
Service is broadly operational but uneven, especially in peri-urban areas. Low-cost fixes are proposed to raise baseline performance and public trust without changing the entire system: (i) Replace containers where overflow and damage are recurrent, especially in underserved areas; (ii) create a simple citizen reporting channel (WhatsApp/phone/web) with public resolution tracking to guide micro-adjustments; (iii) formalize cooperation with neighboring communes (e.g., Sidi Kaouki) to reduce cross-boundary dumping; (iv) deploy more public litter bins in high-traffic areas (including beach frontage) paired with signage and selective enforcement of anti-littering rules. These measures improve equity and satisfaction, but they are not the main lever of system transformation.

Source separation
The absence of separation at source is the single largest blocker to performance, recovery, and landfill control. The plan therefore anchors the whole transition on mandatory, phased source separation, introduced through two pilots projects:

- Ghazoua: 2-stream dry recyclables vs. rest, in partnership with TRIVALDEC and local leaders;

- Diabat: 2-stream organics vs. rest with a neighborhood composting unit.

Pilots are designed to generate operational data (participation, contamination, logistics), refine the model, and build public proof.
Then, source separation should be scaled (district by district over 3–5 years) as such: free, color-coded bins; dedicated collection days/compartments (daily for organics where needed, bi-weekly for recyclables); contract adjustments with ARMA (KPIs, training, awareness budget); continuous education (schools, door-to-door, ambassadors) and graduated enforcement once service is universal.
Incentives emphasize no added cost to households, plus light, community-level rewards (e.g., voucher schemes, public recognition). Crucially, separated streams are visibly and reliably treated to avoid "fake sorting" fatigue.

Treatment & Recovery (strategic direction, details in engineering section)
Decentralized, low-tech initiatives such as community composting and small-scale plastic recycling workshops are encouraged as early recovery actions that create local employment, raise awareness, and demonstrate tangible circular economy benefits. In particular, the establishment of modular "plastic labs" based on open-source technologies from initiatives like Plastic Odyssey and Precious Plastic appears technically and financially viable for Essaouira. These micro-factories can transform locally collected plastic into paving tiles, benches, or panels at relatively low investment cost and short payback periods, offering a pragmatic entry point for community-driven valorization.

However, large-scale diversion ultimately requires centralized treatment capacity. Options such as MBT remain central to medium-term planning (developed in Practical Engineering Solutions), while WtE incineration is not currently relevant for Essaouira. Despite its technical feasibility, the required waste supply ($\geq$50 kt/y) and investment ($\approx$50 MEUR) far exceed local financial and institutional capacities. Even with optimistic electricity revenues, the project would demand gate fees above 100 EUR/t to break even, making it economically unrealistic under current conditions. WtE could be reconsidered only in the long term within a regional or intermunicipal framework once waste quantities, governance, and financing mechanisms are consolidated.

Landfill operations The landfill requires immediate urgent actions in order to remediate it. These priorities include basic compaction, daily/weekly soil cover, perimeter fencing, vector/litter control, and restoring gate control and record-keeping. Gradually phase informal picking from the tip face into safer, supervised sorting roles. Then, we should prepare for structured closure with proper capping and aftercare (detailed engineering below).

7.2 Practical engineering solutions

Here, we present practical engineered solutions that operationalize the strategy, namely (i) a central MBT facility (mechanical line with alternative biological routes), (ii) a robust, multi-barrier leachate treatment train, and (iii) post-closure LFG control (active gas wells with an optional methane-oxidation cap). For each, we provide indicative sizing, process flows, mass/energy balances, and phased implementation to demonstrate technical feasibility within Essaouira's institutional and financial constraints.

7.2.1 Central MBT facility

To provide a backbone for diversion and material recovery, an MBT facility is proposed as the central unit of the future CEV. The design targets a nominal throughput of $\sim$ 40,000 $\mathrm{t\,y^{-1}}$ (with daily peaks of up to $\sim$ 150 $\mathrm{t\,d^{-1}}$), consistent with Essaouira's current and future seasonal flows.

Mechanical pre-treatment and separation

Incoming mixed MSW is unloaded on a controlled reception floor where bulky and hazardous items are removed. The waste is then fed to a primary rotating trommel with 80 mm apertures, producing (i) an organic-rich fine fraction and (ii) an oversize fraction enriched in high-calorific components (plastics, paper/cardboard, textiles, wood). A secondary fines screen at 20 mm removes ultrafines/inerts ($<$ 20 mm, e.g., grit, glass shards), which are unsuitable for biological processing and are directed to landfill. The oversize fraction then passes through metal recovery (overband magnet and eddy-current separator) and an inclusive, ventilated manual sorting line to capture marketable plastics, cardboard/paper, and textiles while formalizing current informal pickers in safer, contracted roles. A negative-pressure wind-sifter subsequently separates the remaining overs into a light, combustible stream (RDF feed) and a heavy inert reject. The RDF stream is conditioned to kiln specifications via slow-speed shredding to $\leq$ 50 mm and baling for off-site energy recovery.

Mass outcomes
At steady state, the MBT mechanical train partitions the mixed input as follows: $\sim$ 61 % ($\approx$ 24.4 $\mathrm{kt\,y^{-1}}$) fines sent to biological treatment; $\sim$ 15–16 % ($\approx$ 6.3 $\mathrm{kt\,y^{-1}}$) as light fraction prepared as RDF; $\sim$ 4–5 % ($\approx$ 1.8 $\mathrm{kt\,y^{-1}}$) as marketable recyclables (plastics, cardboard/paper, metals); and $\sim$ 18.5 % ($\approx$ 7.4 $\mathrm{kt\,y^{-1}}$) as inert residuals (ultrafines and wind-sifter heavies) to landfill. This configuration maximizes diversion of biodegradables and recoverables while minimizing the landfill burden to predominately inert residues.

Biological treatment options for the organic fines

The organic fines stream ($\sim$ 67 $\mathrm{t\,d^{-1}}$ before pre-treatment rejects) is the principal lever for climate and environmental performance. Two proven pathways are considered:

Option A — Anaerobic digestion (AD)
Two variants are suitable at this scale:

(i) **Wet CSTR** operation with a pumpable slurry (10–12 % TS) yields $\sim$ 7,200 $m^3\,d^{-1}$ of biogas at $\sim$ 60 % CH_4, corresponding to $\sim$ 13–14 $MWh_e\,d^{-1}$ and $\sim$ 12–16 $MWh_{th}\,d^{-1}$. Digestate is dewatered to $\sim$ 38 $t\,d^{-1}$ at 25 % TS for use as daily cover/land reclamation, or as a soil amendment where quality allows.
(ii) **Dry AD** (plug-flow or garage type, 25–35 % TS) produces $\sim$ 6,250 $m^3\,d^{-1}$ of biogas, i.e. $\sim$ 11–12.5 $MWh_e\,d^{-1}$ and $\sim$ 11–14 $MWh_{th}\,d^{-1}$, with a stabilized output of $\sim$ 27 $t\,d^{-1}$ at $\sim$ 35 % TS after short post-aeration.

In both cases, AD delivers substantial methane avoidance (by diverting organics from uncontrolled anaerobic decay), on-site renewable electricity of roughly 4.1–5.0 $GWh\,y^{-1}$, usable low-grade heat for process needs (e.g., digestate/RDF drying), and a soil-improving output subject to compliance with agronomic and contaminant standards.

Option B — Black soldier fly (BSF) bioconversion
Following removal of $\sim$ 5 % pre-treatment rejects, $\sim$ 63–64 $t\,d^{-1}$ of OFMSW can be fed to BSF larvae in 12-day cycles under controlled moisture/temperature. Indicative outputs at this scale are $\sim$ 15.8 $t\,d^{-1}$ of live larvae (equivalent to $\sim$ 2.8 $t\,d^{-1}$ of dried meal after processing) and $\sim$ 12.6 $t\,d^{-1}$ of frass requiring stabilization/composting.
This pathway can generate local jobs and circular bio-products (protein/oil) but requires robust colony management, biosecurity, and stable downstream markets.

Programmatic choice

Given Essaouira's scale and need for immediately bankable diversion, deployment should prioritize the mechanical line plus one biological route with high technology readiness and utility-grid value (dry AD), while piloting BSF modularly and integrating it where operational capacity and markets mature.

7.2.2 Landfill Leachate Treatment

Leachate at Essaouira exhibits typical mature characteristics: high salinity and refractory COD (humics/fulvics), low BOD/COD, elevated NH_3-N, and notable metals (especially Cr). Passive lagooning alone is insufficient. A robust, modular train is therefore specified to sequentially remove the dominant pollutant classes and deliver compliant discharge:

1. **Equalization and minor pH conditioning** to buffer hydraulic/quality shocks.
2. **Acidic coagulation–flocculation** (pH 2–3) with DAF/clarification to precipitate humic/fulvic organics early, sharply reducing color and refractory COD while keeping metals dissolved and out of this sludge stream.
3. **Alkaline precipitation** (pH $\sim$10) to remove dissolved metals as hydroxides (e.g., $Cr(OH)_3$); optional sulfide aids for Pb/Cd/Zn co-precipitation; hazardous sludge is stabilized/disposed in a secure cell.
4. **Ammonia stripping** (leveraging pH $\sim$10) in a packed tower with acid scrubbing to ammonium sulfate, typically achieving $\sim$ 70–90 % NH_3 removal.
5. **Advanced oxidation, if needed** (Fenton at pH 2.5–3 with subsequent neutralization and $Fe(OH)_3$ settling) to abate residual refractory COD and micro-pollutants; applied based on effluent targets and receiving-water sensitivity.
6. **Biological polishing** in a simple, climate-suited aerobic system (e.g., aerated lagoon or MBBR) to finish BOD, residual COD, and remaining NH_3.
7. **UF $\rightarrow$ RO desalination** as the terminal barrier: UF protects RO from fouling; RO permeate meets conductivity targets, while brine is sent to solar evaporation ponds with crystalline residues landfilled.

This sequence exploits process complementarity, thereby minimizing overall chemical demand and OPEX for the required compliance. Expected outcomes are: metals within regulatory limits; NH_3-N and BOD/COD reduced to discharge standards; and conductivity controlled via RO, enabling environmentally safe release.

7.2.3 Landfill gas (LFG) management after closure

Modeling of the site's history and decay dynamics indicates a remaining methane generation potential of $\sim$ 6,600 t CH_4 post-2025 if unmanaged ($\sim$ 185,000 $t\,CO_2$-eq, 100-year GWP). Two complementary mitigation measures are proposed.

Primary measure: active gas extraction with controlled destruction or use
A standard wellfield (vertical wells on a 30–50 m grid, HDPE headers, condensate control) connected to a blower

and high-temperature flare (or to CHP sets where feasible) can typically capture ~ 50 % of generated methane over a 30-year aftercare horizon. For Essaouira, this equates to avoiding ~ 3,300 t CH_4 (~ 92,500 t CO_2-eq) and enabling cumulative electricity generation on the order of ~ 13.8 GWh_e if used in CHP. In addition to climate benefits, the project presents realistic opportunities for revenue via electricity sales and, subject to verification and additionality, voluntary carbon credits of order 0.9–2.8 M EUR over the lifecycle, improving financial defensibility of the aftercare program.

Complementary measure: methane oxidation layer (MOL/biocover)
A compost-amended oxidation layer (typically 0.5–1.0 m) encourages methanotrophic conversion of residual CH_4 to CO_2 within the cap. Field efficiencies vary widely (inventory-conservative ~ 10 %, higher under optimized moisture/porosity and low flux). Given Essaouira's dry, windy climate and the risk of preferential pathways, MOLs should be deployed as a *supplement* to active extraction (not a substitute), with attention to irrigation, cover integrity, and maintenance to sustain microbial activity.

7.3 Summary

In sum, improving Essaouira's MSWM requires two complementary layers. **Strategically**, the plan centers source separation as the backbone of the system, launched through focused pilots and scaled citywide with adapted collection, continuous education, light incentives, and graduated enforcement. These measures are supported by pragmatic service fixes for collection and cleanliness, early decentralized recovery efforts for awareness and jobs, and immediate landfill normalization as a bridge to structured closure and aftercare.

Practically, the plan translates into a central MBT facility at the future CEV: a mechanical front-end to separate fines, recyclables, and an RDF stream, paired with biological treatment of organics. Legacy impacts are addressed through a staged leachate treatment train and post-closure gas control. Governance adjustments (contractual KPIs, inclusive formalization of current pickers, secured offtakes, transparent monitoring) complete a phased roadmap capable of shifting Essaouira from reactive disposal to an integrated, circular waste system.

8 Conclusion and Outlook

This thesis set out to answer the main research question: **How can the current municipal solid waste management (MSWM) strategy in the municipality of Essaouira, Morocco, be improved?** Through a comprehensive two-phase approach—diagnostic and strategic—this study provided an in-depth evaluation of the current system and proposed a realistic, phased pathway for improvement.

8.1 Summary of Key Findings

The diagnostic phase, presented in Chapter 4, revealed widespread inefficiencies across all stages of Essaouira's MSWM system. Using literature, fieldwork observations, stakeholder interviews, and performance indicators tailored to the local context, the analysis demonstrated that:

- Waste is not separated at the source, and public satisfaction with collection and cleanliness services is low, especially in peri-urban areas;
- The controlled landfill operates under substandard conditions and is closer to an open dump;
- Recycling activities are restricted to informal and private actors, and waste recovery is very limited
- Legal instruments exist but are not enforced, and awareness efforts remain limited in scope and effectiveness;

The KPI-based evaluation confirmed these findings, with all indicators scoring either *poor* or *mediocre*.

In response, Chapter 5 and 6 presented a series of strategic recommendations with the following key takeaways:

- Source separation is the backbone; pilots de-risk scale-up and keep public trust when paired with visible, reliable treatment.
- A central MBT facility at the future CEV organizes flows: recoverables to markets, organics to biological treatment, residuals to RDF or controlled disposal.
- Decentralized initiatives (composting, micro-recycling) build culture and jobs but must complement—not replace—central capacity.
- Landfill normalization (compaction, cover, fencing, vector control) and leachate and gas control are crucial for a safe closure and aftercare.
- Governance levers matter: awareness campaigns, environemntal law enforcement, transparent monitoring, and inclusive formalization of current pickers.

8.2 Limitations

Data and analytics. Estimates of waste generation, composition, and seasonality are partially reconstructed from heterogeneous sources; the available leachate dataset is dated; and the LFG assessment relies on first-order decay with default parameters. *Mitigation:* install and use weighbridge data as the system of record; run periodic composition studies across seasons (including tourism peaks); update leachate sampling and analysis; and deploy continuous LFG monitoring to recalibrate designs.

Engineering and process performance. MBT performance is sensitive to feed cleanliness and operational discipline; organics can carry grit and plastics that abrade equipment and depress anaerobic digestion (AD) yields; digestate quality depends on contaminants (metals, glass, microplastics); BSF systems at multi–tonne scales require rigorous colony management and biosecurity; leachate trains hinge on tight pH control, oxidant dosing, and membrane fouling management; and methane oxidation layer (MOL) efficiency varies with moisture and gas flux. *Mitigation:* adopt conservative sizing and staged commissioning; strengthen front-end contraries removal (grit traps, acceptance rules); pilot AD/BSF before full roll-out; implement QA/QC for digestate and frass; and protect RO with upstream UF and robust cleaning-in-place protocols.

Markets and offtakes. Prices and specifications for recyclables, RDF, electricity/heat, larvae meal, and compost are volatile; cement kilns may impose stricter RDF quality; grid interconnection and tariffs can cap CHP value. *Mitigation:* secure pre-contracted offtakes with quality specs, price bands, and floor clauses; maintain dual outlets for organics (e.g., AD and composting); retain flaring redundancy for LFG; and develop BSF product markets with appropriate certification.

Institutional and governance capacity. Success depends on contract amendments, steady enforcement (anti-littering, separation mandate), and inter-communal cooperation; political cycles can disrupt continuity. *Mitigation:* formalize roles in a Municipal Waste Management Plan; adopt simple, public KPIs and performance-based payments; and design pilots that are resilient to administrative turnover.

Regulatory environment. Forthcoming EPR schemes, landfill taxes, PET food-contact rules, and carbon-credit eligibility may shift; permitting and EIA timelines can delay projects.

Financial exposure. CAPEX/OPEX rely on scaled references; foreign-exchange risk affects imported equipment; and investment occurs before savings accrue. *Mitigation:* phase procurement, run competitive tenders, include prudent contingencies, pursue blended finance (grants plus concessional loans), and leverage verified carbon/plastic credits where feasible.

Social dynamics. Household participation can regress without visible benefits; enforcement can face pushback; integrating informal pickers requires trust and fair compensation. *Mitigation:* sustain education and two-way feedback (reporting apps with closure of complaints), show tangible recovery outcomes, use community-level incentives, and co-design formalization pathways with current pickers.

Environmental and climate context. Wind and aridity complicate litter control, compost moisture management, and MOL performance; intense rain events can spike leachate flows.

Land and siting constraints. Space for MBT, lagoons/evaporation ponds, and buffers may be limited or contested. *Mitigation:* conduct early site screening, use compact or containerized units where appropriate, and plan multi-use buffers (green belts, education areas).

Stakeholder coordination. Finally, many of the proposed measures—such as source separation pilots, landfill rehabilitation, the establishment of the MBT, and the development of recycling and composting pathways—require the active involvement of multiple actors across public, private, and community spheres. Effective implementation relies on strong cooperation between the municipality, the collection company (ARMA), provincial and national authorities, private recyclers, NGOs, and informal sector representatives. Misalignment of priorities, communication gaps, or limited capacity within any of these groups could slow progress or compromise outcomes. *Mitigation:* establish a dedicated inter-stakeholder coordination platform under the Municipal Waste Management Plan; define clear roles, responsibilities, and timelines; ensure transparent data sharing and feedback mechanisms; and incentivize collaboration through co-funded pilot projects and joint performance metrics.

Taken together, these limitations do not invalidate the proposed pathway; rather, they underscore the need for adaptive management, phased piloting, and transparent performance monitoring to progressively de-risk implementation.

8.3 Future Work

Building on these findings, several avenues for future research and action emerge. First, the analytical basis of this thesis can be strengthened by developing a more robust empirical dataset: continuous weighbridge records, seasonal composition studies, and updated leachate and gas measurements will allow for more precise modelling and planning. Second, technology pilots—such as small-scale anaerobic digestion, black soldier fly composting, MOL test cells, and even source separation—should be carried out under local conditions to assess performance, economics, and social acceptance before scaling up. Third, comparative studies with other Moroccan and international municipalities could help benchmark Essaouira's trajectory and identify transferable best practices. Finally, long-term work should focus on institutional innovation, including governance mechanisms for integrating informal workers, designing effective Extended Producer Responsibility schemes, and developing financial instruments (e.g., plastic or carbon credits) that can sustainably support infrastructure investment. Such research and experimentation will be essential to refine, adapt, and secure the pathway outlined in this thesis.

8.4 Closing Remarks

While Essaouira faces considerable challenges in managing its municipal solid waste, it also has the opportunity to build a locally tailored and forward-looking MSWM strategy. By addressing inefficiencies with targeted, realistic solutions and by leveraging community engagement, the city can move closer to a cleaner, more sustainable future.

”Ultimately, waste is not only a technical issue, but a societal one, reflecting how we value our environment, our institutions, and our collective responsibility.”

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Appendix

A Fieldwork Data Collection Tools

A.1 Interview Guide with Director of Essaouira Beach

1. Beach Management and Tourism

- How is the beach cleaning service organized in Essaouira?
  - Who is responsible for cleaning the beaches (municipality, subcontractor, NGO, etc.)?
  - How frequently is cleaning done?
  - What types of equipment or manpower are used?
- Are there specific measures or additional resources deployed during peak tourism seasons?
- Are there areas of the beach that are more problematic than others in terms of littering or waste overflow?
- Are you aware of recurring behaviors or habits among tourists that contribute significantly to beach pollution?
- Are there public bins on the beach?
  - Are the quantities of waste in these bins monitored?
- Have you observed differences in cleanliness or maintenance between different seasons (e.g., summer vs. off-season)?

2. Public Awareness and Engagement

- Are there awareness campaigns aimed at tourists or residents regarding beach cleanliness or waste prevention?
  - What types of campaigns are organized (e.g., posters, events, beach stands)?
  - Are these campaigns conducted in partnership with schools, NGOs, or other institutions?
  - In your experience, are these awareness efforts effective?
- What are the biggest challenges when trying to raise public awareness about waste on the beaches?

3. Projects & Innovations

- Could you tell us more about the TouMaLi project?
  - What are its objectives, main partners, and current progress?
  - What kind of infrastructure is being developed as part of the project?
  - What types of waste are targeted by the project?
  - Do you have estimated volumes or percentages of waste expected to be recovered?
  - How is the project financed?
  - Are there documents available about this project?
- Is there support available for other pilot or community-based projects related to beach cleanliness or tourism-related waste?
  - Is any municipal or external funding accessible for such initiatives?
  - What criteria increase the likelihood of receiving support for a project?

A.2 Interview Guide with Municipality

1. Governance and Regional Coordination

- Is there a local municipal solid waste management (MSWM) plan as required by Law 28-00 and Law 113-14?
  - If yes, is it accessible to the public?
  - What are the strategic objectives over the next 5 to 10 years?
- Has the commune of Essaouira engaged with the national PNDM program? If so, how?
- Are there partnerships between municipalities within the Essaouira region for waste management?
- Is there a regional or communal waste budget?

2. Budget and Financing

- What is the municipality's annual waste management budget?
- What are the sources of funding (local, regional, national)?

3. Legal and Regulatory Framework

- Beyond Laws 28-00, 113-14, 99-12, 77-15, and 81-12, are there any other important legal texts impacting MSWM in Essaouira?
- How are these national laws applied or implemented locally by the municipality?
- Have you received technical or financial support from the national authorities for implementing these laws?
- What are the main barriers to enforcement or compliance with these laws?
- Regarding Law 77-15 on plastic bags:
  - Why were plastic bags initially reduced and then returned?
  - Is this due to a lack of monitoring, public resistance, or other reasons?

4. Waste Data and Monitoring

- Do you collect data on waste generation, waste composition, or collection?
- Are there annual reports or other documents published on these indicators?
- Do you track performance indicators like recycling rates, illegal dumping, or waste reaching the landfill?

5. Waste Collection

- How is waste collection organized in urban vs. rural areas?
- Do you have estimates of collection rates in rural areas like Ouassane?
- What are the key barriers to effective rural collection?
- Is there a plan to improve collection in rural or underserved zones?
- What is ARMA's scope of responsibility?
- How do you monitor the performance of ARMA?
- Are you generally satisfied with ARMA's performance? Why or why not?
- How do you ensure collection efficiency during peak tourism seasons?

6. Waste Treatment and Disposal

- Are there known illegal dumpsites or "black points" in and around Essaouira?
- What actions are taken to detect, manage, or prevent these?
- Are you satisfied with the current management of the controlled landfill?

- Are there any official reports or evaluations of its performance?
- What is the estimated lifespan of the current landfill?
- Is access by informal waste pickers permitted or tolerated? How is it managed?

7. Public Engagement and Awareness

- Do you conduct awareness campaigns on waste prevention, sorting, or general cleanliness?
- Are these campaigns showing measurable results?
- Do you collaborate with schools, NGOs, or other partners?
- Do you work with informal waste collectors?
  - What is your opinion of their role?

8. Private Sector and Innovation

- Some private actors report difficulties in obtaining municipal support. Why is this the case?
- Are there existing procedures for supporting private or community waste initiatives?
- What type of projects would be more likely to receive municipal backing?
- What kind of budget could be allocated to such support?

9. Projects and Future Developments

- Could you describe the status and vision of the CEV (Centre d'Enfouissement et de Valorisation) project?
  - What are its goals, timeline, and funding structure?
  - Why has the project been delayed?
  - Are there feasibility or environmental studies available?
  - Are there any documents available that you could share?
- When do you estimate the CEV could realistically be operational?

A.3 Interview Guide for Private/Informal Collectors

1. Background

- Can you tell us about your organization's origin and primary mission?

2. Operations

- How do you collect waste?
- How often do you collect waste and how much waste do you collect?
  - Do you notice any difference in volume during tourism peak seasons?
- What type of waste or plastic do you collect?
- How is the waste processed and recycled afterwards?
  - Do you own a recycling plant? Is there one nearby?
  - Do you ship the waste? If so, where?
  - What is done with the end product of the recycled material?
  - What percentage of the collected waste is actually recycled?
- Do you have an estimate of the percentage of waste collected by the informal sector in Essaouira?
- Do you collaborate with local authorities or other organizations for the waste collection and recycling?
  - If not, would you like to? Why?
  - Do you think your work helps compensate for the lack of formal collection systems?

- How do you finance your operations?
- Could you share a list of resell prices for different recyclable materials?

3. **Community Engagement**
   - How do you engage the local community in your initiatives?
   - Are there educational programs or awareness campaigns associated with your work?
   - Do you involve volunteers?
     - How can individuals participate?
   - Do you think there is sufficient awareness in Essaouira regarding plastic waste?
4. **Challenges & Opportunities**
   - What are the main difficulties you face (e.g., logistical, infrastructural, financial, public participation)?
   - What opportunities do you see for expanding or enhancing your impact?
   - What forms of support would be most beneficial to your organization (e.g., funding, volunteers, equipment)?

A.4 Interview Guide Surfrider NGO

1. **Background**
   - Can you tell us about SURF RIDER's origin and primary mission?
   - What inspired SURF RIDER? Why was the project started?
     - Are you satisfied with the current waste management system in Essaouira?
     - Do you think your work helps compensate for gaps in the formal system?
   - Can you share any measurable impacts SURF RIDER has achieved since its beginning?
2. **Operations**
   - How does SURFRIDER organize its beach clean-up activities?
     - How many participants are involved? Which beach areas are targeted?
     - Are all participants volunteers?
     - What are the typical profiles (e.g., age groups) of participants?
   - What is the frequency and typical scale/size of clean-up operations?
     - Are clean-ups more frequent during the tourist season?
   - What type of waste or plastic is most commonly collected?
   - How do you finance your operations?
   - Do you feel your work is acknowledged or supported by the municipality?
3. **Community Engagement**
   - How do you engage the local community in your initiatives?
   - Are there educational programs or awareness campaigns linked to your activities?
     - How often are these campaigns organized?
     - Who are your primary target audiences?
   - Do you collaborate with local authorities or other organizations for these campaigns?
   - Do you think there is sufficient awareness in Essaouira regarding plastic waste?
4. **Challenges & Opportunities**
   - What are the main challenges you face (logistical, financial, infrastructure, participation)?
   - What opportunities do you see for expanding or enhancing your impact?
   - What forms of support are most beneficial to SURF RIDER (e.g., funding, volunteers, equipment)?
   - In your view, what policies or actions should be introduced to prevent plastic pollution more effectively?

A.5 Interview Guide Schools

1. Curriculum and Educational Content

- Do you integrate lessons or activities related to waste, pollution, or the environment into your school curriculum?
  - If yes, what topics are covered (e.g., recycling, plastic pollution, composting), and how often are they addressed (once a year, per trimester, etc.)?
  - If not, why? Would you be interested in introducing courses or workshops on waste management in the future? Would you need support (e.g., materials, guest speakers, teacher training) to start teaching good waste management practices?

2. Practical Activities

- Do students participate in hands-on activities related to waste (e.g., clean-up days, waste sorting, composting, environmental clubs)?
  - If not, would you be willing to introduce such activities?

3. Waste Sorting Infrastructure

- Does your school have waste sorting bins (for plastic, organic waste, paper, etc.)?
  - If yes, do students use them correctly?

4. Awareness Campaign Participation

- Has your school ever participated in awareness campaigns on waste management (e.g., with the municipality, ANP, NGOs)?
  - If yes, which ones? What types of activities were organized?

5. Support and Materials

- Do you receive any materials or support (posters, brochures, videos) from local authorities or organizations to raise student awareness?
- What types of additional resources or support would help you better teach waste management?

6. Student and Family Awareness

- Based on your experience, are students and their families generally aware of good waste practices (e.g., not littering, sorting waste)?

7. Barriers and Challenges

- What are the main obstacles you face when trying to raise awareness about waste management among students in your school?

A.6 Local Population Survey

0. General Information

- 0.1. How old are you?
  - <18 years old
  - 18–30 years old
  - 30–50 years old
  - >50 years old
- 0.2. What is your sex?
  - Male
  - Female
  - Prefer not to say
  - Other

- 0.3. Where do you live?
  - Essaouira (Medina)
  - Essaouira surroundings
  - Sidi Kaouki
  - Ghazoua
  - Diabat
  - Ida Ougourd
  - Other
- 0.4. How many people live in your household?
- 0.5. Do you live in a:
  - House
  - Apartment
  - Riad
  - Other

1. Waste Management Habits

- 1.1. How do you dispose of your waste?
  - Communal containers
  - In front of the house for pick-up
  - Other
- 1.2. Do you separate your waste?
  - Yes
  - No

  If no, why?
  - Not enough information
  - No bins available for separation
  - Not useful in my opinion
  - Other

  If yes, which types of waste do you separate?
  - Plastics
  - Glass
  - Organic waste (food, coffee, etc.)
  - Electronic waste
  - Metals
  - Textile
  - Other
- 1.3. Do you ever throw waste in the street/not in a bin?
  - Yes
  - Yes, when there is no bin nearby
  - Yes, if the bin is full
  - Yes, when no one is watching
  - No

2. Access to Equipment

- 2.1. Are there enough communal containers near your home?
  - Yes
  - No
- 2.2. How far do you have to go to dispose of your waste?
  - In front of my house
  - Less than 100 meters
  - Between 100 and 500 meters
  - Between 500m and 1 km
  - More than 1 km
  - I don't know / It changes
- 2.3. What condition are the communal containers generally in?
  - Good / Empty
  - Damaged
  - Overflowing
- 2.4. How often is waste collected in your neighborhood?
  - Every day
  - 3–4 times a week
  - 1–2 times a week
  - Less than once a week
- 2.5. Is that enough in your opinion?
  - Yes
  - No
- 2.6. On a scale from 1 to 5, how satisfied are you with the current waste collection system?
- 2.7. Could you explain?

3. Property & Environment

- 3.1. Do you observe waste-related problems in your area?
  - Dirty streets
  - Open dumps
  - Odors
  - Stray animals
  - No problem
  - Other
- 3.2. On a scale from 1 to 5, how clean do you consider your neighborhood/city to be?
- 3.3. Could you explain?
- 3.4. Are there public bins in your city?
  - Yes, plenty
  - Yes, but not enough
  - No

4. Awareness and Participation

- 4.1. Have you ever received instructions on waste management and sorting?
  - Yes

- No

If yes, how?

  - Social media
  - Posters
  - Flyers
  - School
  - Local meetings
  - Other

- 4.2. Would you like more information about:
  - Sorting waste
  - Recycling
  - Composting
  - None
  - Other

- 4.3. Would you be willing to:
  - Sort/separate your waste using 2–3 bins
  - Participate in beach clean-up activities
  - Join a local composting project
  - Not interested in any of these

B Source separation Pilot Project Cost estimates

B.1 Cost estimates Pilot project for recyclables in Ghazoua

Table 21: Estimated costs for the recyclables pilot project in Ghazoua (100 households)

Cost Item	**Estimated Cost (MAD)**	**Explanation**
Bins or bin liners	2,000–10,000	Two bins or liners per household (blue for recyclables, grey for rest); cost varies based on material quality (basic bags vs. plastic bins).
Flyers / awareness materials	1,000–3,000	Printed flyers with pictograms and instructions; based on local printing costs (approx. 2–3 MAD per flyer).
Door-to-door outreach	750–2,500	Potential compensation for local volunteers or students (approx. 50 MAD/day/person); may vary depending on duration and staff.
Events (kickoff + midterm)	2,000–4,000	Small launch and midterm events to build visibility and community buy-in.
Monitoring tools	500–1,500	Printed surveys and/or SMS reminders to participants; approx. 1 MAD per SMS and 2 MAD per survey.
Miscellaneous (Fuel transport, etc)	1,000	Signage for bins (labels, pictograms), transport of bins or materials, minor logistical expenses not included elsewhere.
Total (estimated)	**10,000–20,000**	Rounded estimate for entire 6-month pilot implementation.

B.2 Estimates for Pilot project for organic waste in Diabat

Table 22: Estimated Cost and Impact of Composting Pilot Project

Metric	**Scenario 1: 50 HH**	**Scenario 2: 100 HH**
People involved	200	400
Food waste (40% (low) participation, kg)	8,640	17,280
Food waste (60% (high) participation, kg)	12,960	25,920
Total compost input (low, kg)	28,800	57,600
Total compost input (high, kg)	43,200	86,400
Compost output (low, tons)	11.52	23.04
Compost output (high, tons)	17.28	34.56
Potential revenue (low, MAD)	5,760	11,520
Potential revenue (high, MAD)	8,640	17,280
Total cost (MAD)	**16,900**	**22,300**
Composting units needed	3	5

Cost Breakdown (in MAD):

- **Household bins (30L)**: 50 × 50 = 2,500 | 100 × 50 = 5,000
- **Communal containers (120L)**: 3 × 300 = 900 | 6 × 300 = 1,800
- **Composting boxes**: 3 × 1,000 = 3,000 | 5 × 1,000 = 5,000
- **Tools (forks, gloves, thermometer, etc.)**: 2,000
- **Signage and educational boards**: 500
- **Awareness campaign (flyers, meetings)**: 2,000
- **Training (for operators/teachers)**: 1,000
- **Site preparation (fencing, shading, leveling)**: 5,000

C LCV for each type of waste

Table 23: Waste composition and estimated calorific values

Waste Type	**Share (%)**	**Estimated LCV (MJ/kg)**
Oragnics	61	4
Fines < 20 mm	9	2
Plastics	9	35
Cardboard	3	24
Papers	2	22
Textil sanitary	3	10
Textile	2	16
Composit	1	12
Glass	2	0
Metals	1	0
Classified combustibles	1	10
Non-classified combustibles	4	0
Hazardous waste	2	0

The average lower calorific value is calculated using a weighted sum:

$$\text{LCV}_{\text{avg}} = \sum_{i=1}^{n} (w_i \times \text{LCV}_i)$$

Substituting the values:

$$
\begin{aligned}
\mathrm{LCV}_{\mathrm{avg}} &= (0.61 \times 4) + (0.09 \times 2) + (0.09 \times 35) + (0.03 \times 16) + (0.02 \times 15) \\
&\quad + (0.03 \times 10) + (0.02 \times 16) + (0.01 \times 12) + (0.01 \times 10) \\
&= 2.44 + 0.18 + 3.15 + 0.48 + 0.30 + 0.30 + 0.32 + 0.12 + 0.10 \\
&= \boxed{7.39 \text{ MJ/kg}}
\end{aligned}
$$