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A Review Study on Designing a Modern, Environmentally Friendly Landfill Using a Lining System

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Abstract: This study presents an inclusive review and proposed design for a modern, environmentally friendly landfill utilizing an advanced lining system to mitigate the environmental impacts of municipal solid waste (MSW). The research focuses on the implementation of a dual-liner system, combining bentonite clay for its high absorption capacity with a high-density polyethylene (HDPE) membrane, to prevent leachate leakage and groundwater contamination. The design also incorporates a gravel layer with embedded pipes for efficient leachate collection, directing it to a treatment facility for purification. Daily soil cover is applied to minimize odors and pests, while a final capping system, including a geomembrane and soil layer, ensures long-term environmental protection.

The study highlights the urgent need for sustainable waste management solutions in Sirte, Libya, where uncontrolled dumping poses significant health and environmental risks. By analyzing climatic conditions, waste composition, and population growth projections, the proposed landfill design addresses local challenges while adhering to international standards. Key outcomes include reduced greenhouse gas emissions, minimized leachate infiltration, and the potential for land reclamation post-closure, transforming the site into usable green spaces.

1. Introduction

Waste takes many forms, including municipal solid waste (MSW), biodegradable waste, non-biodegradable waste, chemical waste, construction and demolition waste, electronic waste, biomedical waste, wastewater, toxic waste, industrial waste, and food waste (Chaoton et al., 2018). Among these, solid waste has emerged as one of the most significant challenges facing urban communities today, with severe local environmental and socioeconomic impacts that become particularly evident when waste accumulates uncontrolled in yards, open lands, and streets. These random dumping sites not only contribute to water, air, and soil pollution but also create ideal breeding grounds for disease-carrying insects, rodents, and birds while simultaneously reducing the value of nearby properties. In response to these pressing issues, numerous scientific studies have focused on developing sustainable policies for integrated and environmentally friendly waste management solutions (Zohoori & Ghani, 2017). Currently, several waste disposal methods are employed worldwide, ranging from incineration and composting of biodegradable waste to recycling programs and - most relevant to this study - sanitary burial in carefully engineered landfills designed for specific waste types (Drunner & Keller, 1972). The urgency of proper waste management is vividly illustrated in Fig.1, which shows scattered waste plaguing neighborhoods and streets in Sirte Municipality, demonstrating the critical need for effective waste management systems.

Figure 1. Random waste in some streets of Sirte Municipality (General Company, 2022).

2. Study Objectives:

This study comprehensively studies the design of modern sanitary landfills with a focus on eco-friendly lining systems to mitigate environmental impacts. Through a systematic review of global best practices, it evaluates important components—including liner materials (e.g., compacted clay, HDPE, GCLs), leachate collection, and gas recovery systems—while integrating a case study analysis of [Sirte city] to assess real-world performance. The research highlights how climate-specific challenges (e.g., monsoons, droughts) influence liner durability and landfill efficiency, proposing adaptive designs such as composite liners for extreme weather and enhanced leachate treatment. The findings aim to guide policymakers and engineers in implementing next-generation landfill systems that balance environmental protection, regulatory compliance, and operational feasibility.

3. Research Problem:

This study addresses the critical absence of a scientific framework for waste disposal system design in Libya, with particular focus on Sirte Municipality. Current waste management practices rely on collecting and dumping waste in uncontrolled, unsanitary landfills, demonstrating fundamental weaknesses in solid waste management infrastructure. These systemic inefficiencies originate from three key shortcomings: insufficient data collection, inadequate documentation processes, and the lack of comprehensive, science-based planning methodologies.

4. Municipal Solid Wastes (MSWs)

Solid waste (SW) refers to any discarded materials in solid or semi-solid form, originating from residential, commercial, industrial, agricultural, and institutional sources (Kumar, 2016). Its improper management poses significant environmental and public health risks, including pollution, disease vector proliferation, and resource depletion (Othman, 2022). Table 1 shows the different sources of SWs generation (Kumar, 2016).

Table 1. summarizes the primary sources and composition of SW (Kumar, 2016).

Source	Waste Generation Sites	Types of Solid Waste
Residential waste	Homes, apartments	Food waste, paper, plastics, glass, textiles, metals
Commercial waste	Offices, hotels, markets, hospitals	Paper, packaging, food scraps, electronics
Industrial waste	Factories, refineries, power plants	Metals, ash, hazardous chemicals, wood, plastics
Construction/Demolition	Building sites, road repairs	Concrete, steel, wood, rubble
Municipal services	Parks, streets, beaches	Garden trimmings, sweepings
Agricultural waste	Farms, processing plants	Crop residues, pesticides, animal manure

4.1 Major Categories of Municipal Solid Waste:

i. **Household Waste** defined as waste generated from homes, which can often be processed for reuse for the same or different purposes. Examples include paper, cardboard, newspapers, magazines, aluminum materials such as soft drink cans, broken glass, plastic, furniture, and used clothes. It is classified according to its components as follows (Slack et al., 2004):

- **Organic waste**: Decomposable waste such as food scraps and garden waste.
- **Inorganic waste**: Waste free from organic compounds, such as plastics, metals, furniture, and fabrics.

ii. **Construction Waste** primarily includes inorganic materials such as stone and concrete, as well as organic materials like wood. It has a minimal environmental impact since these materials have limited or no decomposition ability. Construction or demolition activities typically generate this waste (Ahmed, 1996).

iii. **Hazardous Waste** originates from various industrial and commercial activities and has physical or chemical properties that are dangerous to human health and the environment. This waste must be disposed of in specialized landfills. Operators must properly identify hazardous materials, as these cannot be discarded with non-hazardous municipal waste. Improper disposal can cause serious environmental and health issues (Ananza, 2002). Hazardous waste is defined by properties such as corrosiveness, reactivity, flammability, and toxicity. According to American and European Union environmental protection laws, waste is classified based on various reactions and tests, as shown in Table 2. Some household products contain hazardous chemicals, as shown in Table 3.

Table 2. Reactions and tests used to classify hazardous waste (Ananza, 2002).

Interaction	Description
Flammability	Wastes are hazardous if flammable with a flash point below 140°F, produce sparks, or are oxidizers.
Corrosion Susceptibility	Hazardous if the pH is 2 or lower, or 12.5 or higher.
Reactivity	Reactive if unstable, reacts violently with water, produces toxic gases, or can easily decompose/explode.
Chemical Toxicity	Toxic if elements exceed specified standard levels. Tested by the Toxicity Characteristic Leaching Procedure (TCLP).

Table 3. Examples of Hazardous Materials from Household Waste (Shah & Shaikh, 2008).

Consumable Material	Resulting Hazardous Waste
Pesticides	Organochlorine and organophosphate compounds.
Plastic	Organochlorine compounds, organic solvents (especially in PVC).
Pharmaceuticals	Organic solvents, low concentrations of heavy metals.
Paints	Heavy metals, dyes, solvents, organic residues.
Batteries	Heavy metals such as lead and cadmium.
Petroleum Derivatives	Oils, organic compounds, phenols, heavy metals, ammonia, salt acids.
Minerals	Heavy metals, dyes, corrosive salts, oils, phenols.
Leather	Heavy metals.
Furniture	Dyes, heavy metals, organochlorine compounds.

iv. **Agricultural Waste** encompasses crop residues, animal manure, and hazardous agrochemicals such as DDT and nitrates (Obi et al., 2016). A particularly pressing issue is the global accumulation of obsolete pesticides, with developing nations facing severe environmental risks - Ethiopia alone stores more than 1,500 tons across 400 contaminated sites, many perilously close to water sources (Shah & Shaikh, 2008). These stockpiles contain extremely toxic compounds including chlordane, dieldrin, and PCBs, which are linked to fatal diseases and congenital disorders. Paradoxically, despite well-documented health dangers, some malaria-endemic regions still rely on DDT due to limited affordable alternatives. The agricultural chemical burden extends to nitrogen-based fertilizers, where excessive nitrate contamination in water supplies poses multiple health threats: it compromises children's eye health, disrupts blood oxygenation, and catalyzes the formation of carcinogenic nitrosamines (Shah & Shaikh, 2008).

v. **Industrial Waste (IW)** poses significant environmental and public health risks due to its toxic chemical composition, which can lead to groundwater and surface water contamination. This waste stream frequently contains decomposable organic matter that, when left untreated, creates multiple secondary hazards including noxious odors, insect breeding grounds, and rodent infestations (Dadwal & Singh, 2023). The diversity of hazardous industrial byproducts is demonstrated in Table 4, which catalogs dangerous waste types from various manufacturing sectors, ranging from heavy metals in metalworking industries to halogenated solvents from paper production. Particularly concerning are the persistent organic pollutants and corrosive substances that can persist in ecosystems for decades, creating long-term contamination challenges even after waste disposal operations cease (Matavos-Aramyan, 2024). The improper management of these industrial byproducts not only threatens immediate water quality but can also disrupt entire food chains through bioaccumulation of toxins, underscoring the critical need for stringent industrial waste treatment protocols and containment measures (Singh et al., 2024).

Table 4. Industrial Sources of Hazardous Waste (Shah & Shaikh, 2008).

Industrial Source	Type of Hazardous Waste
Metal Industries	Solvents, strong acids/bases, paint waste, heavy metals, cyanides, oils, flammable and reactive waste.
Chemical Industries	Chlorinated solvents, acids/bases, heavy metals, flammable and organic waste.
Detergent and Soap Industry	Solvents, acids, alkalis, heavy metals.
Tanning and Leather Factories	Heavy metals, acids, alkalis, organic waste.
Paper Making	Halogenated solvents, corrosive waste, dye waste.

vi. **Electronic Waste (EW)** comprises discarded electrical and electronic equipment, including computers, televisions, mobile devices, batteries, and audio equipment (Ankit et al., 2021). The rapid pace of technological advancement and frequent device upgrades have led to staggering quantities of e-waste - the United States alone generated 3 million tons in 2003. This waste stream presents both significant environmental challenges and valuable recovery opportunities, as it contains toxic substances like lead (718,000 tons from PCs between 1994-2003), mercury (287 tons), and cadmium (1,363 tons) alongside precious metals including gold and copper (Misra & Pandey, 2004). Particularly concerning are the health risks posed by hazardous components such as PVC, arsenic, and cobalt, which contrast sharply with the potential for resource recovery from these complex waste materials.

vii. **Medical Waste:** Medical waste is hazardous due to its high toxicity, chemical contaminants, radioactive elements, and disease-causing potential. It includes waste from isolation rooms, sterilization and disinfection byproducts, blood, plasma, surgical fluids, contaminated instruments (needles, scalpels, syringes), and pharmaceutical industry waste (Ommar et al., 2024; Shah & Shaikh, 2018).

5. Solid Waste Landfills

The concept of landfilling has evolved significantly from basic waste burial to sophisticated engineered systems. While historically any waste disposal site with daily cover qualified as a "sanitary landfill," modern standards require comprehensive engineering controls to mitigate environmental and public health impacts (Vesiline et al., 2002). This evolution reflects growing understanding of waste management challenges and technological advancements.

5.1 The Persistent Problem of Open Dumping: Open dumping remains prevalent in developing nations, characterized by unplanned waste deposition without environmental safeguards (WHO, 2001). These uncontrolled sites exhibit multiple hazards (Ferronato & Torretta, 2019; Gulnihal et al., 2021):

- Unrestricted acceptance of mixed waste types
- Chronic waterlogging and leachate formation
- Groundwater contamination through unlined bases
- Frequent uncontrolled fires contributing to air pollution
- Complete absence of engineered protection systems

Figure 2. An example of open dumping (Ozbay et al., 2021).

As shown in Fig. 2, such dumps represent significant environmental liabilities requiring urgent remediation. The absence of basic infrastructure like liners or drainage systems creates long-term contamination risks that often persist for decades after site abandonment.

5.2 Modern Sanitary Landfill Engineering: Modern sanitary landfills incorporate multiple engineered systems including compacted waste layers with daily cover, composite liners, leachate collection networks, gas extraction systems, and hydrological controls (Fig.3). The conventional "dry tomb" approach minimizes moisture to reduce leachate but slows decomposition (Sharma & Reddy, 2004), while newer bioreactor designs accelerate decomposition through leachate recirculation, offering 30-50% faster stabilization, reduced post-closure periods, improved gas capture, and better space utilization (Reddy & Bogner, 2003). These engineered systems must include composite liners, leachate treatment, gas management, and cover systems (Reinhart & Townsend, 1998), representing a paradigm shift toward sustainable waste management that balances containment with active decomposition (Tchobanoglous et al., 1993).

Fig. 4 illustrates a model bio-sanitary landfill, demonstrating the three principal bioreactor landfill configurations: anaerobic, aerobic, and hybrid systems. In anaerobic bioreactors, oxygen-independent microorganisms progressively break down organic matter through acidogenesis followed by methanogenesis, ultimately generating methane (CH_4) and carbon dioxide (CO_2) as primary byproducts. Conversely, aerobic systems utilize oxygen-dependent microbial communities that oxidize waste primarily into CO_2 and water vapor. Hybrid bioreactor landfills strategically combine these biological processes, initially employing aerobic decomposition to accelerate waste stabilization before transitioning to anaerobic conditions for methane recovery (Sharma & Reddy, 2004). This integrated approach optimizes both decomposition rates and energy recovery potential while minimizing environmental impacts through controlled biological treatment of landfilled waste.

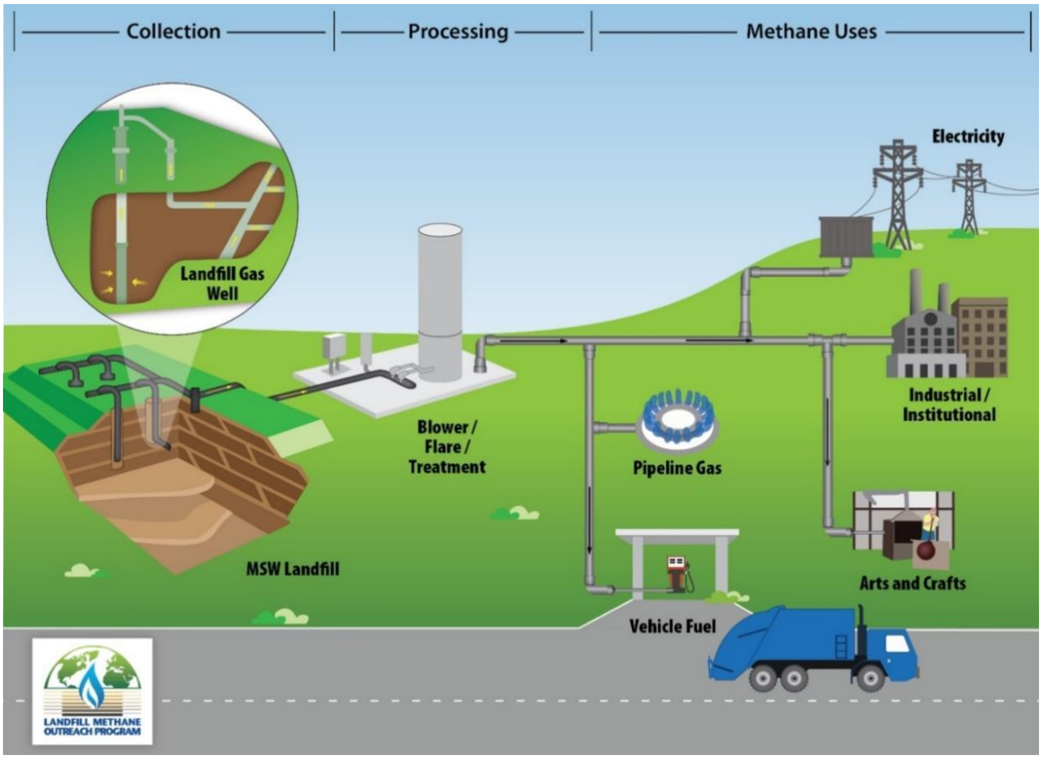

Figure 3. Plan for a fully sanitary municipal solid waste landfill (Review, 2022).

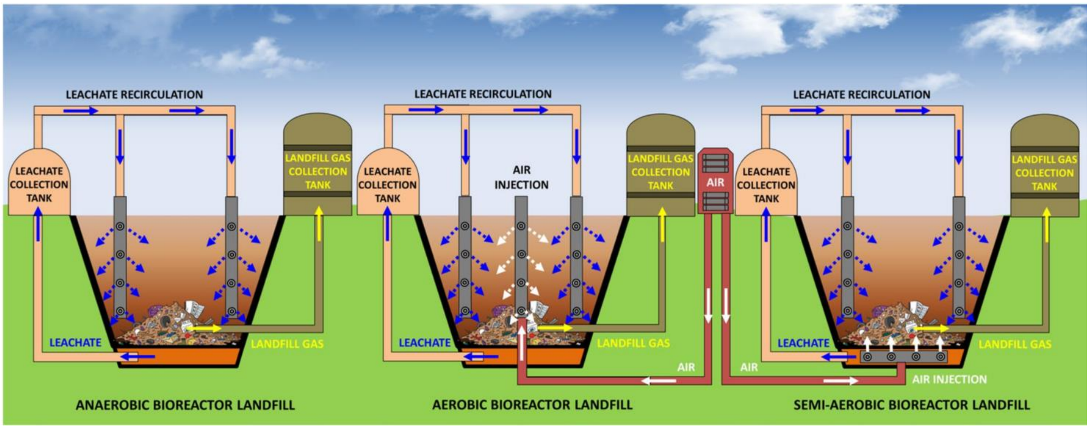

Figure 4. Illustrates a model bio-sanitary landfill (Nanda & Berruti, 2020).

5.3 Design Features of a Sanitary Solid Waste Landfill

The critical differences between sanitary landfills and open dumps begin with their fundamental governance and design. Sanitary landfills are government-regulated facilities operating under strict engineering supervision, implementing daily soil cover to control pests and odors, while open dumps represent unauthorized, unmonitored disposal sites lacking any environmental controls (Al-Wabel et al., 2022). Central to modern landfill engineering is the lining system, which serves as the primary barrier against leachate migration and gas emissions (Tchobanoglous et al., 1993).

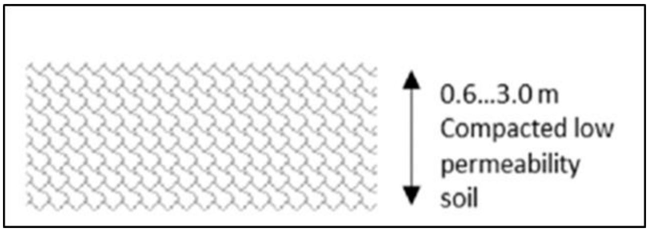

Figure 5. The compacted clay lining (Tuomela et al., 2021).

These systems must achieve hydraulic conductivity below 10^{-7} cm/s, employing various configurations: single-component clay liners using natural materials like compacted clay; enhanced mixtures such as cement-stabilized red mud from alumina production (Osinubi & Eberemu, 2013) or bentonite-sand composites that balance low permeability with crack resistance (Sivapullaiah et al., 2000; Kleppe & Olson, 1985); and multi-layer systems including double liners with leak detection, composite geomembrane-soil combinations, and specialized double-composite systems for hazardous waste. Flexible membrane liners (FMLs) – manufactured from materials ranging from butyl rubber to various polyethylenes (HDPE, LDPE) and engineered polymers (CPE, ELPO) – provide additional containment options, either as standalone barriers or integrated with clay layers as whown in Fig. 5 (Syed et al., 2024). This engineered approach contrasts sharply with open dumps' complete absence of containment, highlighting the technological sophistication behind modern waste containment strategies.

5.3.1 Leachate Formation and Management: During waste decomposition, biological reactions produce acidic fluids that combine with infiltrating water to form leachate—a highly toxic, dark-colored liquid with a strong odor. As leachate percolates through the waste mass, it accumulates suspended solids, dissolved contaminants (Vesiline et al., 2002), organic and inorganic compounds, and pathogens such as bacteria and viruses (Crowley et al., 2003). Its composition varies based on waste type, landfill age, compaction density, and site hydrology, while its strength is typically measured through BOD, COD, or TDS levels. Under acidic conditions, leachate may also contain heavy metals like lead, cadmium, copper, and zinc (Table 5). Effective leachate management requires minimizing water infiltration through proper waste sorting (to exclude wet materials) and rigorous surface water monitoring in high-rainfall regions. Typical pollutant concentrations range widely—for instance, BOD levels span 1,000–30,300 mg/L, while metals like lead remain below 1.0 mg/L (Lee & Jones, 1993).

Table 5. Common pollutants and compounds found within landfills (Lee & Jones 1993).

Parameter	Typical Range (milligrams per liter, unless otherwise noted)	Upper Limit (milligrams per liter, unless otherwise noted)
Total Alkalinity (as $CaCO_3$)	730–15,050	20,850
Calcium	240–2,330	4,080
Chloride	47–2,400	11,375
Magnesium	4–780	1,400
Sodium	85–3,800	7,700
Sulfate	20–730	1,826
Specific Conductance	2,000–8,000 µmhos cm^{-1}	9,000 µmhos cm^{-1}
TDS	1,000–20,000	55,000
COD	100–51	99,000
BOD	1,000–30,300	195,000
Iron	0.1–1,700	5,500
Total Nitrogen	2.6–945	1,416
Potassium	28–1,700	3,770
Chromium	0.5–1.0	5.6
Manganese	Below detection level – 400	1,400
Copper	0.1–9.0	9.9
Lead	Below detection level – 1.0	14.2
Nickel	0.1–1.0	7.5

5.3.2 Leachate Treatment System: Leachate treatment, which can be conducted either on-site or off-site (Fig. 6), requires careful system design tailored to the specific contamination levels present (Regional Center, 2005). The treatment approach must account for three critical factors: (1) the chemical composition and flow rate of the leachate, which vary significantly based on landfill age and waste type; (2) comprehensive treatability studies to evaluate the most effective treatment methods prior to implementation; and (3) additional testing to account for potential variations in leachate characteristics over time (Clemente et al., 2024). These considerations ensure the selected treatment system can effectively handle the complex mixture of organic compounds, inorganic salts, and potential heavy metals typically found in landfill leachate, while remaining adaptable to changing conditions throughout the landfill's operational life.

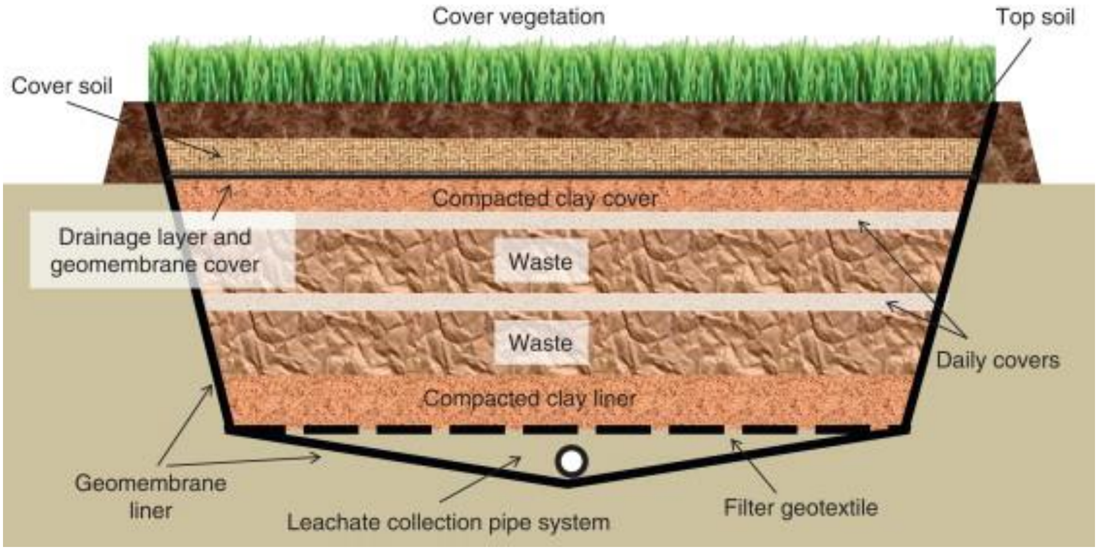

Figure 6. Model of a landfill including a leachate treatment system (Muralikrishna & Manickam, 2017).

5.3.3 Landfill Gas Generation and Impacts: Landfill gas, a natural byproduct of anaerobic and aerobic biological decomposition, primarily consists of methane (CH_4, 50-60%) and carbon dioxide (CO_2, 30-40%) (Yaashikaa et al., 2022). This gas mixture poses multiple environmental and operational challenges when not properly controlled. Mechanically, accumulated gas can compromise landfill structural integrity by eroding cover systems. Ecologically, it creates anoxic soil conditions that suppress root respiration and vegetation growth. From a safety perspective, methane concentrations between 5-15% in air create explosive atmospheres, while both CH_4 (with 28-36 times the global warming potential of CO_2 over 100 years) and CO_2 contribute significantly to climate change (Methane Emissions, 2025). Notably, while anaerobic processes dominate methane production, aerobic decomposition concurrently generates CO_2, making comprehensive gas collection systems essential for mitigating these multifactorial risks across all landfill operational phases. Additionally, when waste contains sulfur (common in certain foods and plastics), specialized bacteria can generate hydrogen sulfide (H_2S)—a toxic gas with a foul odor—posing further health risks (Kunak Technologies S.L, 2025).

6. Literature Review: Previous Studies on Sanitary Landfills

Numerous studies have investigated sanitary landfill solutions for solid waste management, offering valuable insights for developing countries. Five particularly relevant case studies include:

i. **Southern West Bank Solid Waste Management Project (Palestine)**: This regional landfill serving Hebron and Bethlehem Governorates. The main design features of the landfill included a length of 750 meters, width of 370 meters, a total area of 2504 hectares, and 20.4 hectares dedicated to the landfill. The site was divided into four development phases (each consisting of two cells), with each phase having a filling life of 5 years. The maximum waste height was set at 40 meters. The final design included a ground lining system, leachate and gas collection and treatment systems, surface water management, external insulation, access roads, administrative buildings, a maintenance workshop, and a leachate storage tank (Palestinian Authority, 2009).

ii. **Weltevreden Landfill Gas Study (South Africa)**: A study describes the Weltervreden landfill, located in the Polokwane Municipality. The landfill spans 35 hectares with a slope of approximately 56% from the base. Its elevation is 14 meters on the west side and 11 meters on the south side. The site is enclosed by a fence to prevent unauthorized access. Additionally, a water tank sprinkler system sprays water regularly to suppress dust. The landfill has an average depth of 65 feet, and simulation software (LandGEM and Afvalzorg) was used to estimate methane gas (CH_4) production. According to the 2023 projections, methane emissions were estimated at 4,613 Mg/yr (LandGEM) and 3,128 Mg/yr (Afvalzorg). For the period from 1999 to 2050, the total projected gas production was 25,111,799 Mg/yr (LandGEM) and 9,327,898 Mg/yr (Afvalzorg) (Njoku & Edokpayi, 2022).

iii. **Kureepuzha Bioreactor Landfill (India)**: Kollam was chosen to design the Kureepuzha landfill as an alternative to open burning to handle the city's solid waste. The project guidelines outlined the requirements for constructing a sanitary landfill, including a leachate management and monitoring system, as well as a liner system consisting of a 30 cm thick drainage layer made of soil with a permeability greater than 2-10 cm/s, a 20-30 cm thick protection layer, a 1.5 cm thick geomembrane or more, and a 1 m thick compacted clay barrier or modified earth barrier with a permeability less than 10 cm/s. It also specified that a leachate treatment system should be provided, with the type of treatment chosen depending on the properties of the materials within the leachate. The methodology followed for designing Kollam 's modern landfill was an anaerobic bio-based municipal solid waste (MSW). The landfill's active life was set at 5 years, and its post-closure period was 10 years. Each phase was considered as one year. Each stage is divided into 365 cells, with waste being refilled daily and covered daily. Humidity within the cells is maintained through leachate recycling and a gas collection system (Mobern, 2022).

iv. **Calgary Biocell (Canada)**: The Calgary Biocell demonstrated the feasibility of biocell operations in extremely cold temperatures. Located within the Shepard landfill in Calgary, the groundwater table lies about 3 meters below the surface, creating a gradient that reduces the risk of leachate contamination. The collection system included a gravel drainage layer, a leachate basin, a geocomposite on slope areas, and a drainage trench leading to a 0.6-meter-deep leachate basin filled with gravel. Leachate was collected using 200 mm HDPE pipes capable of removing up to 48.8 m^3/day. These pipes, laid in gravel-filled trenches, had a bore diameter of about 15 mm. The leachate basin was a cast-in-place concrete structure with dimensions of 2.44 x 2.44 meters and a depth of 8.5 meters. In addition to the basin's 23.8 m^3 storage capacity, the gravel and trench system offered an additional 390 m^3 of storage (Hettiarachchi et al., 2013).

v. **Fakse Landfill (Denmark)**: This landfill located in the southeastern part of Zealand, Denmark, the Fakse Municipality landfill consists of two sections. The first section, the focus of this study, was active from 1981 to 1997. The second section became operational in 1998 and is expected to be in use until about 2040. The first section covers 12 hectares, with a total capacity of 760,000 m^3, of which 660,000 m^3 were used. An additional 140,000 tons of waste are located in the western part of the second section. The landfill features a 15–20 m thick clay layer serving as the bottom liner, which was supplemented with compacted clay in some areas. Above the liner is a 0.3 m gravel drainage layer with PVC drainage pipes (diameter 95–130 mm), spaced 15–20 meters apart, connected to an inspection well. The leachate is transported to a wastewater treatment plant (Fredensslund et al., 2007).

7. Liner System in Landfills

The liner system serves as the critical barrier against soil and groundwater contamination while enabling effective leachate collection and removal. Modern landfill designs typically incorporate multilayer composite liners combining clay and synthetic materials to create impermeable zones that isolate waste from the surrounding environment (Meegoda et al., 2016). As demonstrated in the Davis Landfill case (Fig. 7), which handles methane-generating waste streams (Davis Landfill, 2022), this study proposes an enhanced double composite liner system rather than a single composite design. This configuration provides redundant protection through:

1. **Primary and Secondary Leachate Collection Systems**:
   - Ensures complete leachate removal
   - Provides backup containment in case of primary system failure (Woodard & Curran, 2006; Onyelowe et al., 2021)
2. **Hazardous Waste Considerations**:
   - When accepting mixed household waste without recycling pretreatment
   - Requires classification as hazardous leachate landfill
   - Mandates double composite liner systems in base construction (The Encyclopedia, 2015; Fig. 8)

The double composite design (Figs. 9) represents industry best practice for high-risk scenarios, offering multiple failure prevention mechanisms through its layered geometry and redundant collection networks. This approach significantly reduces contaminant migration risks compared to single-layer systems while accommodating the full waste decomposition lifecycle, including methane production.

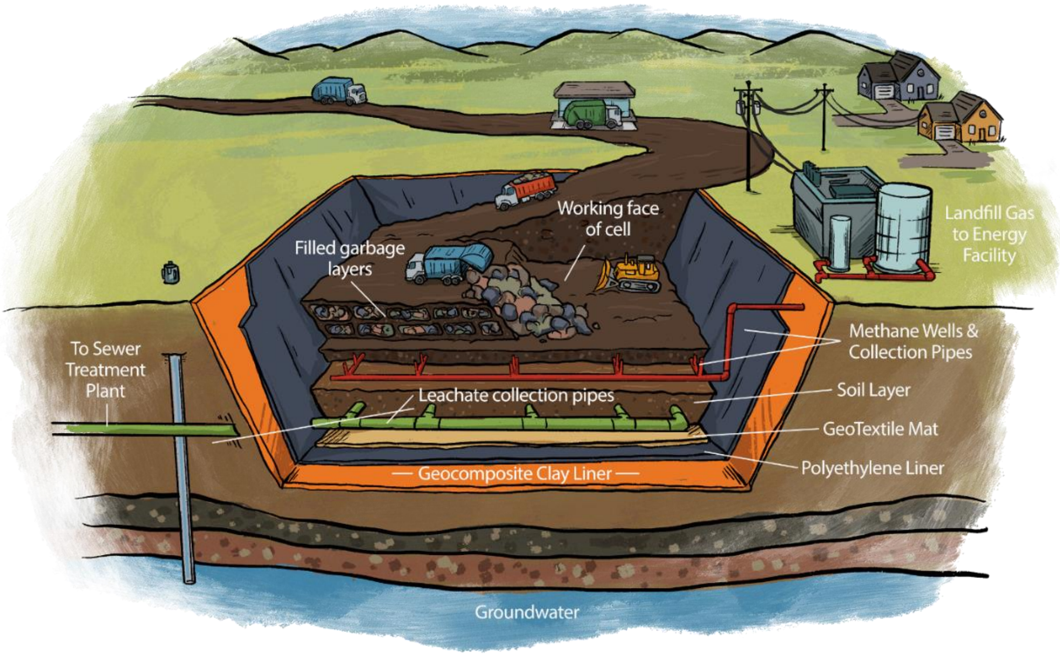

Figure 7. Schematic diagram of the Davis Landfill layers (Davis Landfill, 2022).

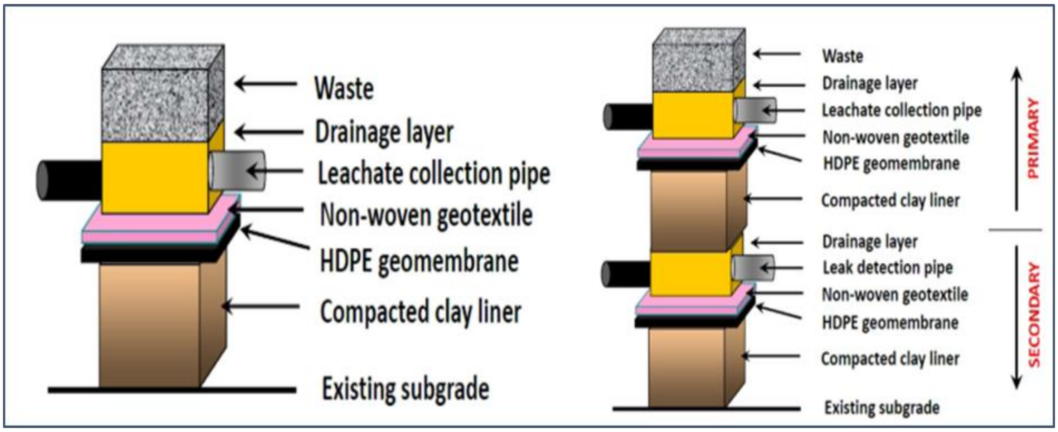

Figure 8. Illustration of a landfill liner system: double composite and single composite (Karunaratne et al., 2001).

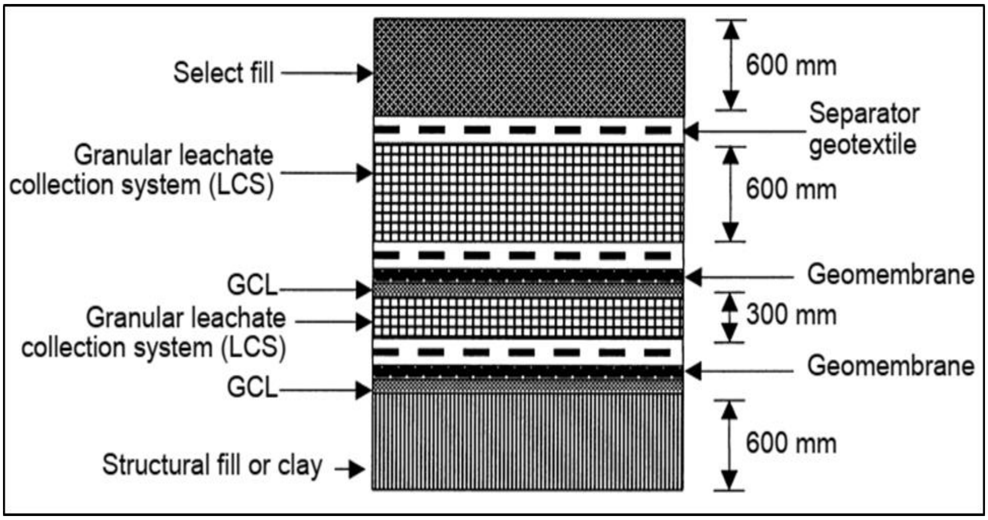

Figure 9. Schematic diagram of the layers of a double-lined landfill in a bottom liner system for hazardous waste (Karunaratne et al., 2001).

7.1 Components of the Proposed Landfill Layers in a Dry Climate

The proposed landfill consists of several layers from bottom to top:

i. **Bentonite Clay Layer:** Bentonite is a natural clay primarily composed of montmorillonite, typically yellowish-white in color, and derived from volcanic ash. Its structure is a sheet silicate, allowing it to absorb water and exhibit base-exchange properties (The Encyclopedia, 2015). Sodium bentonite can absorb up to 10 times its weight in water and swell up to 18–25 times its dry volume (Fig. 10). Its colloidal properties make it suitable for applications like foundry molds, animal feed, drilling muds, and soil improvement (Woodard & Curran, 2006).

Figure 10. Sodium Bentonite Clay – Fine (Bentogard, 2025)

When mixed into soil, bentonite reduces the soil's hydraulic conductivity. Upon contact with leachate, it swells and seals the pores, making the layer less permeable (Bentogard, 2025). The clay liner's thickness typically ranges from 1–1.5 meters based on international standards for composite liner systems. The design may use Darcy's Law:

$$T = \frac{KH}{Q}$$

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Where: **T** = thickness of the liner, **K** = hydraulic conductivity, **H** = head of the leachate above the liner, **Q** = flow rate of leachate, **H/T** = hydraulic gradient (Iyyanki & Valli, 2017).

For slope stability, proper clay properties and moisture content must be ensured. The subgrade must be well-compacted: the first layer should be 200–250 mm thick (compressed to 150–200 mm), with subsequent layers around 150 mm (compressed to 100 mm) (Iyyanki & Valli, 2017).

ii. High-Density Polyethylene (HDPE) Liner

This synthetic liner consists of HDPE membranes with a minimum thickness of 2.0 mm, placed above the compacted soil and joined at the site (Fig. 11). A composite lining of 60 cm bentonite and an 80-mil HDPE membrane is common (Stegmann, 1990). HDPE is widely used due to its low cost, excellent chemical resistance, and UV durability. It is suitable for applications like landfill liners and water containment (Gao et al., 2022). According to international standards (Iyyanki & Valli, 2017), HDPE liners must:

Figure 11. Using of HDPE liner in landfill design (Karunaratne et al.,

- Be 1.5–2 mm thick
- Be chemically compatible with landfill leachate and gases
- Withstand overburden pressure
- Minimize welded joint connections

iii. Leachate Collection and Drainage Layer (LCRS)

Leachate is the liquid formed from rainfall and waste decomposition (Fig. 12). The collection system directs leachate to a central basin for proper removal (Ramke, 2019). A well-functioning LCRS is crucial for long-term liner performance. Materials must withstand extreme leachate chemistry and high temperatures (typically 15–40°C in municipal solid waste landfills). According to international specs, LCRS systems must meet the following requirements (Table 6):

Figure 12. A picture of the raw juice (black liquid) and then after treatment (pure water), (Leachate, World's first landfill leachate, 2025)

Table 6. Specifications for Leachate Drainage Systems

Drainage layer	Thickness	≥ 30 cm
	Hydraulic conductivity:	≥ 1.10 m/s
	Drainage material (grain size):	Gravel 16–32 mm
Drainage pipes	Inside diameter	≥ 300 mm

Slopes	Drain spacing	≤ 30 m
	Cross slope	≥ 3%
	Longitudinal slope	≥ 1%

A system of perforated PVC pipes (Fig. 13) must be installed in the drainage layer with proper slope for continuous flow. Regular inspection and cleaning are essential (Golhosseini et al., 2023).

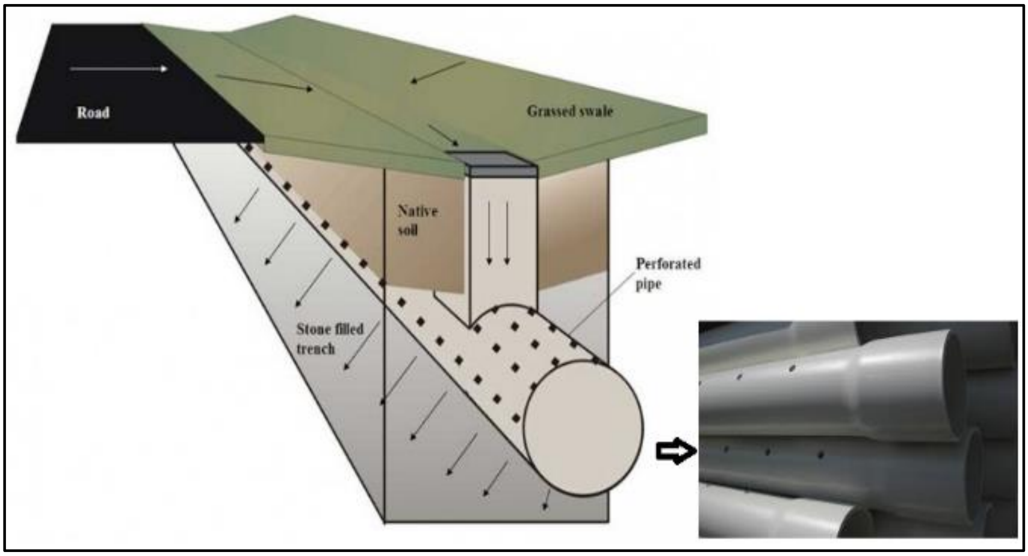

Figure 13. Perforated PVC pipe for landfill leachate collection (Municipal Servicing, 2025).

To avoid leachate accumulation, it must be quickly conveyed using drainage materials such as gravel and perforated pipes (Fig.14). Pipe diameter should be at least 150 mm, surrounded by 40 mm gravel (Bazienė et al., 2012) (Fig. 15).

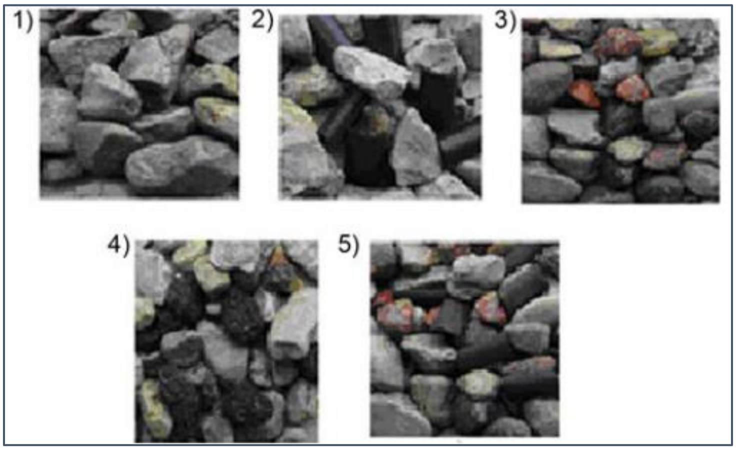

Figure 14. Materials used for filling the drainage layer: 1 - Drainage aggregate, 2 - Aggregate mixed with rubber waste, 3 - Screened gravel (size 35-62 mm), 4 - Aggregate mixed with asphalt waste, 5 - Gravel mixed with rubber waste (Chandrasena et al., 2019).

iv. Municipal Solid Waste Cells

The landfill surface is divided into cells (Figs. 16 & 17), where waste is deposited and compacted daily (Fig. 18). At the end of each day, waste is covered to deter pests, minimize odors, and prevent fires (Guion, 2022). Traditionally, a 6-

inch daily soil cover is used. Alternatives like sprayed paper emulsions, geotextiles, ash, or shredded tires are also used to save space (Zafar, 2024). Cell dimensions depend on expected waste volume and truck traffic. Typically, cell height is 2–3 meters, and the overall landfill may rise 15–20 meters above ground level (Landfill Cap Barriers, 2025).

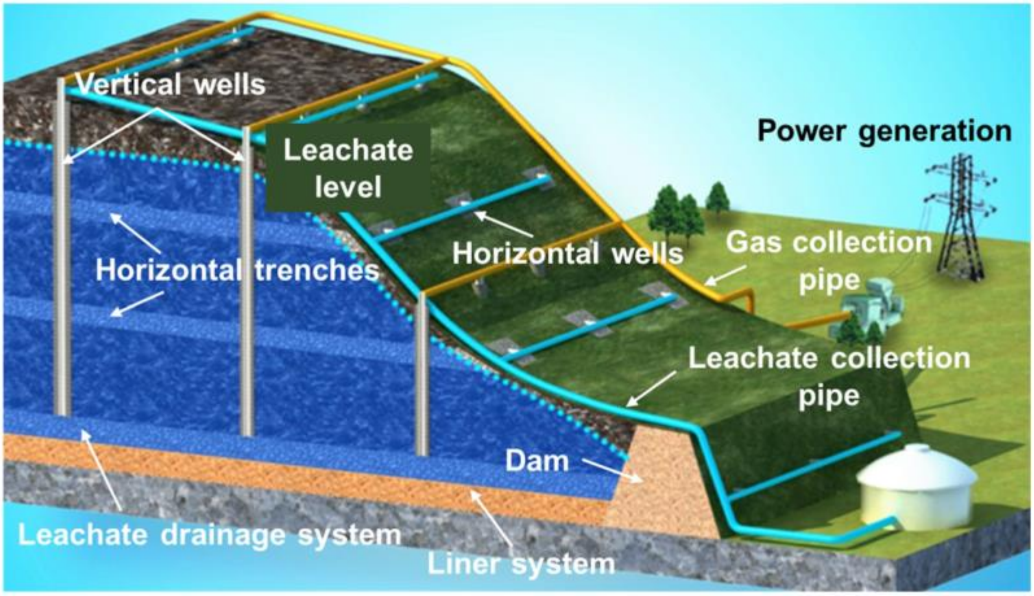

Figure 15. Schematic of leachate collection pipe in a landfill (Chen et al., 2021).

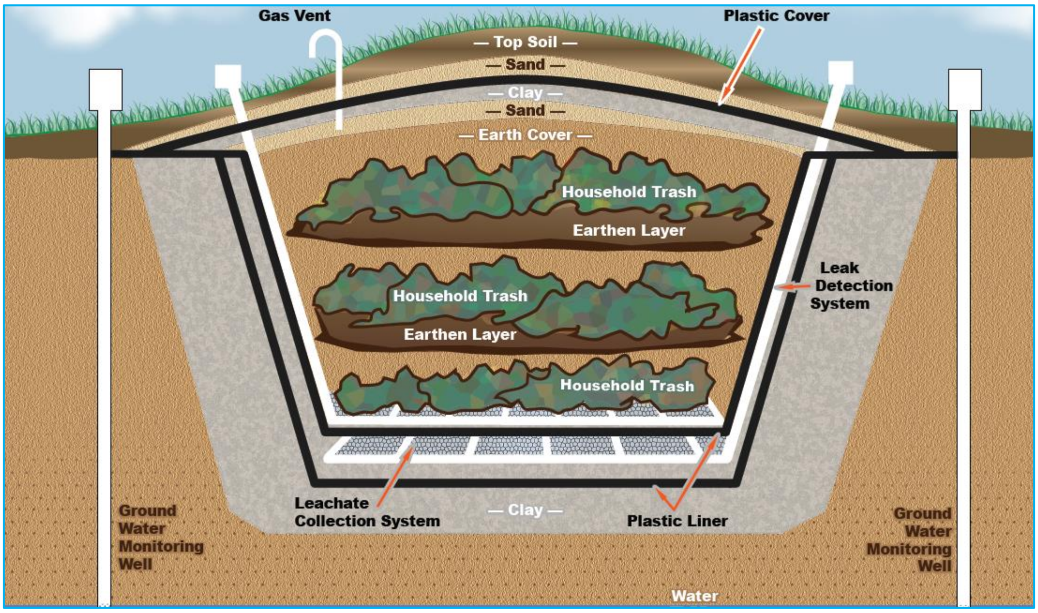

Figure 16. Diagram showing the position of old cells (bottom) and new cells (top) in the landfill (Education, 2022).

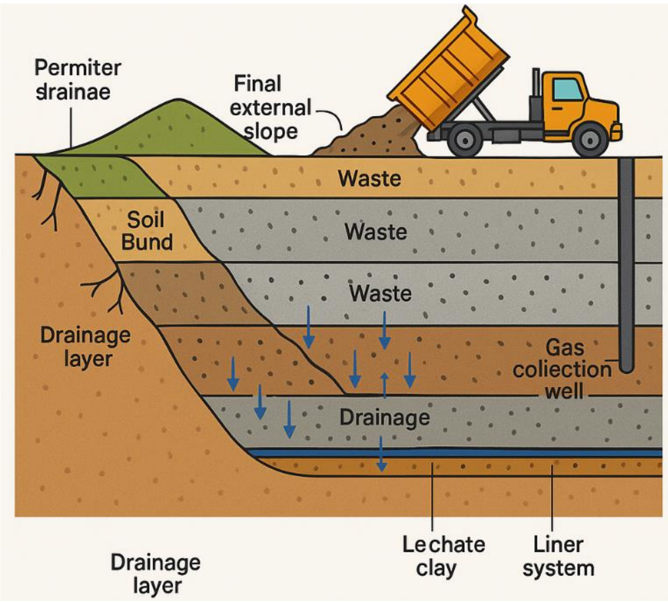

Figure 17. A picture showing the operation of compactor tractors periodically to reduce the volume of waste (Guion, 2025).

Figure 18. a diagram showing the daily cover of each cell with a layer of soil (Hadi, 2025).

v. Final Landfill Cap

Grass Covering: After closure, grass turf is added (Fig. 19), allowing the site to be repurposed as a park, field, or green space. Final covers must meet safety and durability standards, with an expected service life of 100 years. Reuse of closed landfills is growing in importance.The landfill's final cover system must comply with international standards such as the EU Landfill Directive, which mandates a dual-component barrier consisting of a geosynthetic clay liner (GCL) overlain by a high-density polyethylene (HDPE) geomembrane. Modern solutions like Bentofix® GCL provide superior engineering performance by

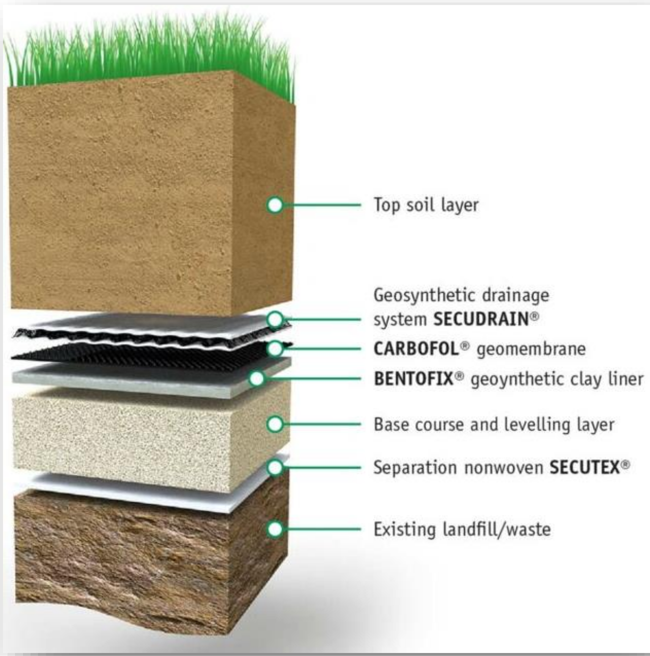

Figure 19. Diagram of final landfill cell cover (Naue, 2025).

integrating these critical components into a single, pre-fabricated layer that combines the impermeability of bentonite clay (swelling up to 18-25 times its dry volume upon hydration) with the durability of synthetic membranes. This innovative composite material achieves the required hydraulic conductivity of ≤10^{-9} m/s while simplifying installation and ensuring long-term protection against leachate infiltration and gas migration, addressing two of the most persistent challenges in landfill closure and post-closure management.

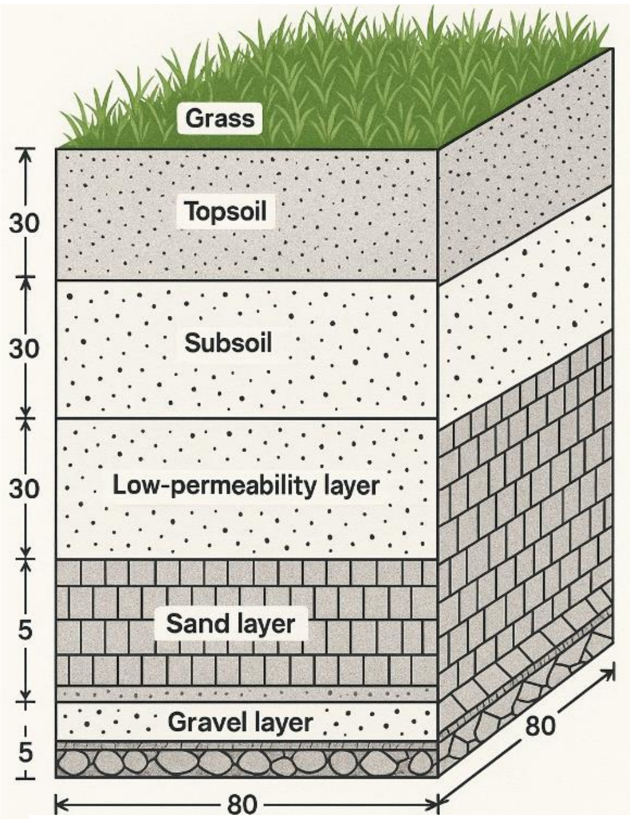

Figure 20. showing the structure of a sanitary landfill covering system (Sinnathamby et al., 2013).

The cross-sectional diagram (Fig. 20) showing the structure of a sanitary landfill covering system designed to safely contain waste and prevent environmental contamination. It includes the following clearly labeled layers (from top to bottom). Grass (surface grass) which is the topmost layer that helps reduce erosion and adds aesthetic and environmental value. Topsoil (30 cm) that supports plant growth and contributes to biological processes like decomposition. Subsoil (30 cm) provides stability and further supports vegetation. Low-permeability layer (30 cm) – typically composed of clay or synthetic materials to prevent water infiltration and leachate escape. Sand layer (5 cm) – assists in drainage and protects the lower gravel layer. Gravel layer (5 cm) – facilitates leachate collection and drainage. The total thickness is 130 cm (1.3 meters), and the base area shown is 80 cm by 80 cm, representing a modular unit of the capping system. The diagram uses distinct textures and colors to differentiate materials and enhance clarity (Sinnathamby et al., 2013). This system ensures environmental protection, slope stability, and sustainable land reuse

Summary of important layers:

- **Carbofol® HDPE Membranes**: Used alone for inert waste, or combined with a clay liner for municipal and hazardous waste. These membranes provide chemical resistance and long service life (Fig. 21).

Figure 21. Image showing Carbofol® HDPE lining membranes (Acar, 2025)

- **Bentofix® GCLs**: Two geotextile layers encapsulate swelling sodium bentonite. Their needle-punched structure ensures durability and self-sealing properties (Fig. 22). They outperform traditional clay liners, especially on steep slopes (Landfill Cap Barriers, 2025).

This system ensures environmental protection, slope stability, and sustainable land reuse.

Figure 22. Image showing Bentofix® geosynthetic clay liners (GCLs), (LMI Group, 2024).

8. Study Area

The city of **Sirte** is located on the Mediterranean Sea and overlooks the gulf that shares its name. It covers an area of approximately 77,660 square kilometers. Geographically, Sirte lies at latitude 19°12′31″N and longitude 18°35′16″W. The coastal regions of Sirte Municipality experience moderate, temperate weather for most of the year. In contrast, inland areas are characterized by extreme heat in the summer and extreme cold in the winter. The average annual rainfall varies significantly—from 200 mm along the coastal strip to as little as 50 mm in the semi-desert areas further inland (Abu Madina, 2017).

8.1 Population Growth

Population data for the years **2019 to 2022** were obtained from the **Sirte Civil Registry**. The annual **population growth rate** was calculated using the following formula (Calculating Growth Rates, 2025):

$$Growth\ Rate = \left(\frac{\text{Population of current year} - \text{Population of previous year}}{Population\ of\ previous\ year}\right) x\ 100$$

Table 7. Population Growth Rate Data for Sirte (2019–2022)

Year	Number of Males	Number of Females	Total Population	Growth Rate (%)
2019	69,480	67,560	137,040	—
2020	69,850	67,940	137,790	0.5472
2021	70,834	68,477	139,311	1.1038
2022	71,304	68,931	140,235	0.6632

Using the 2022 population growth rate, the projected population over the next 20 years was estimated in Excel:

- Projected Population (2042): 163,524.8

This indicates a continuous acceleration in population growth, as illustrated in Fig. 23. As the population increases, the volume of solid waste also grows, since waste generation is directly related to per capita waste production. According to the United Nations, the average individual in a developing country produces approximately 470 kg of waste per year (Al-Alami Fawaz, 2020).

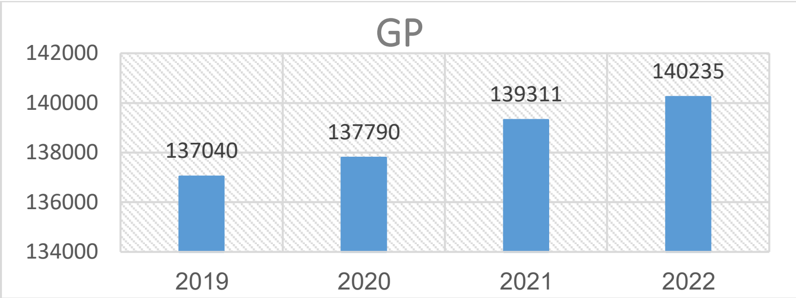

Figure 23. Acceleration of population growth in Sirte (2019–2022)

9. Discussion

This study presents the design of a comprehensive sanitary landfill system for household solid waste, with particular emphasis on preventing soil and marine contamination through effective leachate containment. While sustainable sanitary landfills (Fig. 24) represent one of the most cost-effective disposal solutions for developing regions, their successful implementation faces significant challenges - primarily stemming from low public awareness of integrated waste management principles and limited private sector investment in recycling infrastructure due to weak institutional enforcement. The big problem of the different waste can lead to big issues (Fig. 25). The absence of recycling systems in Sirte specifically necessitates the use of specialized double composite liner systems to safely contain the resulting hazardous leachate (The Encyclopedia, 2015).

These technical solutions must be complemented by robust public education campaigns across multiple media platforms to promote proper waste disposal practices and highlight the environmental consequences of improper management. The proposed landfill design thus addresses

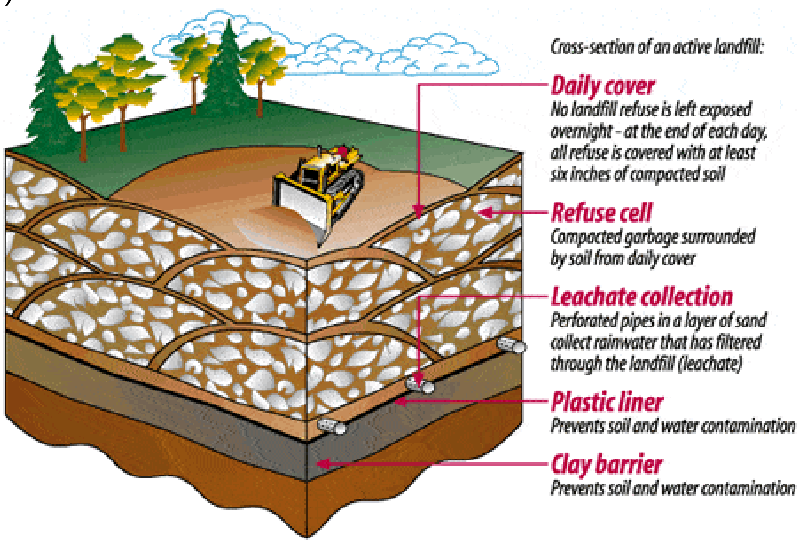

Figure 24. Cross-section of an active landfill (Bluewater Recycling, 2017)

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both engineering requirements and the socio-institutional barriers to effective waste management in the region.

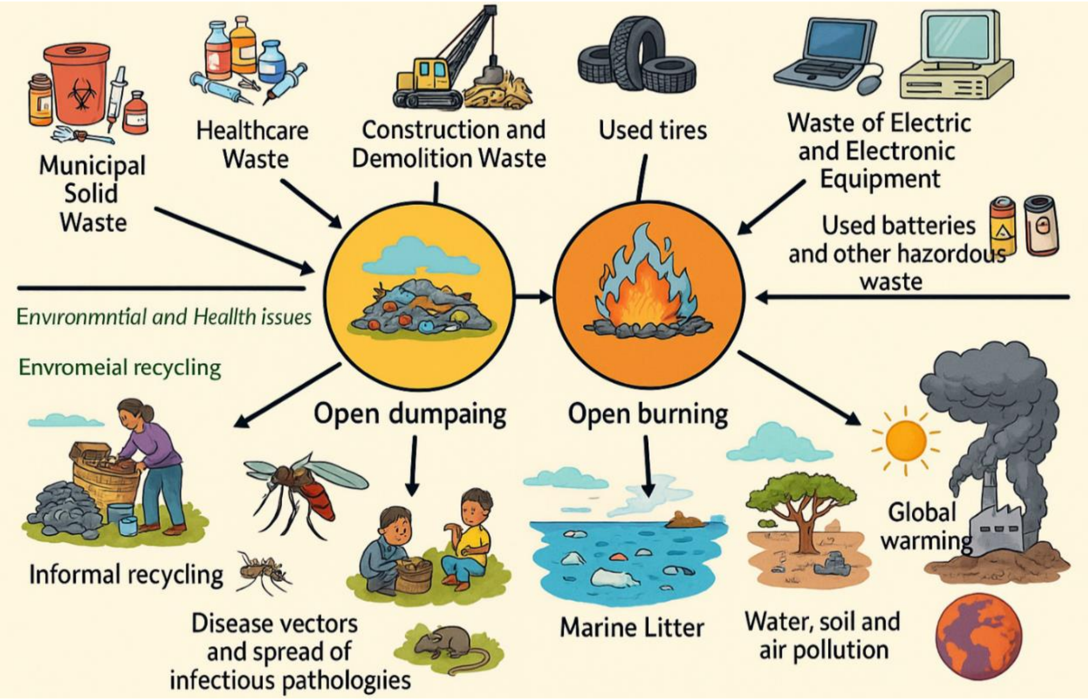

Figure 25. Environmental and health impacts of improper waste management practices (Ferronato & Torretta, 2019).

10. Recommendations

To effectively mitigate environmental and public health risks from solid waste, this study proposes an integrated set of evidence-based measures beginning with operational improvements including the implementation of color-coded separation containers (green for organic, blue for recyclables, red for hazardous waste) to enable source segregation, mandatory use of covered transport vehicles to prevent litter dispersal, and establishment of fixed collection schedules to minimize accumulation. For site management, we recommend locating processing/storage facilities at least 500 meters from water resources, installing 2.4-meter perimeter fencing with wildlife deterrents to restrict animal access, and prohibiting landfill siting within 1 kilometer of residential areas or sensitive facilities like hospitals and schools. These physical measures should be supported by policy interventions including financial incentives for private sector recycling initiatives, integration of waste management education into school curricula, and implementation of strict penalties for improper disposal, creating a comprehensive framework that addresses both immediate operational needs and long-term behavioral change.

Conflict of Interest: The authors declare that there are no conflicts of interest.

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