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Landfills in the Context of Municipal Solid Waste Management in Lebanon: A review focusing on Greater Beirut Area

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Abstract

Municipal solid waste management has long been an unresolved problem in Lebanon. Management strategies were crisis-ridden instead of being proactive and sustainable. The history of this sector in Lebanon is highly dictated by the political unrest in the country, weak governance, and late public awareness of the environmental impact of waste generation and disposal. These factors have imposed the only alleged management option adopted by the public sector which is centralized landfilling that covered 50 % of the country and persisted for 30 years. With the chapter on the mega-landfills coming to an end, this report's objective is to describe the landfilling systems as there is a lack of published data on them. Furthermore, the overreliance on landfills through continuous land exploitation is extending their lifespan momentarily especially since unsorted wastes are being disposed of further to the Beirut blast explosion year 2020. The methodology of data compilation was from published articles accompanied by regular visits to the landfills' managing entities. Open dumping and burning of waste have so far prevailed over sanitary landfilling and waste recovery. Thus, there is an urgent call to divert waste from chaotic open disposal and then divert waste from landfills as much as possible. It can be concluded that the application of integrated solid waste management law 80 that encourages waste minimization techniques through sustainable practices related to reusing and recycling waste is of crucial importance. Additionally, and with the scarcity of published data on landfills, this review hopes to lead to communication among Lebanese citizens and stakeholders and with other countries to exchange both scientific and practical experiences.

Keywords: *Lebanon, Environment, Solid waste management, Landfills.*

1. Introduction

The constant accumulation of solid waste in the environment calls for unprecedented measures. Although environmental awareness has encouraged sustainable behavior, the rate of diffusion of municipal solid waste has always exceeded its rate of reuse and recovery (Rezaeisabzevar et al., 2020; Morales, 2020). Globally, most waste (37%) is dumped in landfills and 33% is disposed of in open dumps (Kaza et al., 2018). The Arab countries are considered one of the world's highest per capita waste generators. The United Arab Emirates achieved a municipal solid waste generation per capita of 2.2 kg which is amongst the highest rates worldwide followed closely by Qatar, Kuwait, Saudi Arabia, Oman, and Bahrain. Hence, around 150 million tons of total urban waste are generated in the Gulf Cooperation Council (GCC) annually, with municipal solid waste being the second largest stream after construction and demolition wastes (Mani, 2020). Thus, the sight of wastes dumped in open spaces, deserts, and water bodies is very common due to the deficiency of garbage collection and disposal facilities in addition to a lack of awareness towards waste management and a lack of research on solid waste (Zyoud et al., 2015). Open dumps host potential pathogenic microorganisms which contaminate the soils posing major public health risks (Eghomwanre et al., 2020). Several factors contributed to the ascending waste crisis in the GCC such as rapid urbanization, a construction boom, industrial growth, and improved lifestyle. The organic material constitutes the greatest portion of the wastes in the Gulf states followed by a major part of recyclables. Interestingly, Lebanon shares with the UAE having high waste recovery rates (23 and 27% respectively) (Thabit et al., 2023). Although the countries in the MENA region have similar waste constituents, their methods of landfilling MSW are various (Jaradat and Al-Khashman, 2013). Landfilling of wastes remains the most practiced disposal method.

In Lebanon, solid waste management (SWM) continues to be a complex issue due to deficit implementation of modern SWM practices, non-uniform governmental plans, inadequate environmental awareness, and lack of governmental support (MoE/GFA/EU, 2017; MoE/UNDP/GFA, 2017; MoE/UNDP/ECODIT, 2011). Additional challenges in the SWM sector are the immigration of Syrian refugees year 2011, poor legislative framework, and lack of law enforcement (De Quero-Navarro et al., 2020; MoE/UNDP, 2017; MoE/EU/UNDP, 2015).

Municipal solid waste (MSW) makes up about 90% of

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the total solid waste generated in Lebanon. MSW's average generation per capita is 1.05 kg/d. The high production rate, 1.2 kg/d, mainly corresponds to the region of Beirut and part of Mount Lebanon. Organic wastes are the largest component of the waste stream averaging 53% followed by potentially recyclable material (31%) then other wastes (16%). As for municipal waste collection, the coverage is high, reaching 99% (Sweep-net, 2014). Only 15% of the waste is treated in sorting facilities where material recovery and composting occur. The private sector has failed to shift from a high percentage of disposal to the recovery of both energy and materials (CDR/LACECO, 2011). Around 50 facilities currently exist throughout Lebanon, however, not all of them are operational and/or functioning efficiently (MoE/UNDP/GFA, 2017).

Greater Beirut Area alone generated 51% of the total MSW generated in the country (MoE/GFA/EU, 2017). The Country Report on Solid Waste Management in Lebanon estimated that Lebanon generated 2.04 million tons of Municipal Solid Waste in 2013.

Until the year 2016, only two sanitary landfills for municipal solid waste, Naameh, and Zahle, were under operation and only 23% of national MSW was being recovered by composting and recycling (Sweep-net, 2014). Only a few non-sanitary landfills were constructed yet around 941 open dumpsites are now spread across the country (MoE/UNDP/ELARD, 2017). The latter receives 50% of the total waste while 30% reaches sanitary landfills (MoE/UNDP/GFA, 2017). The climax of ill management of the waste sector was manifested in the waste piling up in the streets in the regions of Beirut and Mount Lebanon after the closure of Naameh Landfill in 2015. The only other sanitary landfill is Zahle Landfill in the Bekaa district which by now has reached 20 years of operation. It is located in a secondary city but favored by the sense of responsibility of the municipal council and the professionalism of the operator (World Bank, 2007).

The current state of the solid waste sector is a consequence of the history of the solid waste crises and three sectors: the formal sector restructuring itself to ensure a basic service, informal actors compensating the gaps left by the central system through resource recovery, and the decentralized sector trying to provide an alternative to the centralized one. However, total efficiency is being held back as these sectors need yet to cooperate (Azzi, 2017). The ratification of the integrated solid waste management law (Law Number 80) in 2018 pushed discussions relating to the decentralization the MSW management services (MoE, 2018). A recent study foresees a strong viability of the success of the decentralization of MSW management services (Abed Al Ahad et al., 2020). The problems facing Lebanon in the solid waste management sector are the exact ones that the GCC and/or Arab countries are facing and similar solutions can be applied to the Middle Eastern Countries. Furthermore, this sector suffers from the scarcity of reliable and accurate background data and information that one can build upon for the creation of sustainable future strategies and solutions.

Studies by Sawaya et al., 2021, Khadra and Stuyfzand 2014, and Fadel et al., 2002 tackled pollution as a result of leachate infiltration into water resources. Other studies about the composition of municipal solid wastes were demonstrated through papers by Mokbel et al., 2022 and Halwani et al., 2020. However, none of the undertaken studies encompassed the prime landfills with all their aspects while shedding light on the basic problems facing this sector with adequate solutions.

Thus, this paper provides a thorough brief on the waste management status in Lebanon with an emphasis on landfills in the context of individual landfill design and characteristics. As the waste crisis is repetitively reoccurring, and as the landfilling solution is the only disposal mode adopted throughout the years, the landfills in Lebanon are being overexploited. This overreliance is being additionally demonstrated after the Beirut blast year 2019 leading to the entry of unsorted wastes into the landfills. Thus, this literature is crucial as it reveals the successful and unsuccessful experiences of the landfills which will allow enhancement of the landfill statuses via possible future upgrading of the technical and environmental features of the landfill sites and/or landfill mining. Furthermore, it will highlight the need to adopt an overall sustainable waste management strategy.

1. History of Solid Waste Management

During the period 1900-1975, the responsibility of waste collection, treatment, and disposal was endorsed to municipalities. However, even then, the practices were described as unsatisfactory and uncoordinated. The period of the civil war (starting the year 1975) is considered the turning point for the waste collection industry.

1. 1975–1990: Civil War era

Circumstances of war split regions from each other. Most of the country's infrastructure was ravaged whereby solid waste facilities including refuse collection trucks, containers as well and other waste-related equipment were destroyed and/or nonfunctional due to the complete absence of maintenance. Jumbled waste disposal actions were taking place with the intermingling of wastes from hospitals to hazardous and others (World Bank, 1995). Two coastal dumpsites were created in the Normandy and Bourj Hammoud areas which received Beirut's municipal and destruction wastes. As for the areas outside the capital, municipal collection, and uncontrolled dumps were the dominant practices.

During 1987 and 1988, around 15800 illegal toxic waste barrels were exported from Italy to Lebanon. (Hägerdal, 2021). Those barrels contain highly toxic substances such as explosive nitrocellulose; outdated adhesives, organophosphate pesticides, solvents, as well as outdated medication; oil residues, and heavy metals (Holder, 1995). In 1989, an agreement referred to as Taef (Saudi Arabia) was signed and was considered the foundation for ending the civil war and restoring political normalcy to the distorted country.

2. 1990–2015: the post-war era or Sukleen's monopoly

The war created vast economic and social wounds. Therefore, the country witnessed the creation of organizations that aimed to manage reconstruction and state reform. The key ones are the Council for Development and Reconstruction (CDR) and the Office of the Minister of State for Administrative Reform (OMSAR). These institutions today are responsible for the implementation of the Council of Ministers' decisions via conducting public tendering to plan, design, and build the country's main facilities.

The waste collection and dumping sectors did not improve during the first years after the war. Waste was deposited in bags at street corners and was picked up sporadically by trucks. Domestic wastes were mixed with hazardous and hospital ones. Also, the usual dumpsites were utilized and the compiled waste was often put on fire as a consequence of infrequent collection (World Bank, 1995). The resumption of adequate waste collection services was adopted the year 1994 due to private sector contracting. This is the result of the international aid provided through the NERP (National Emergency Recovery Program) coupled with the extensive efforts of the CDR. Sukleen, which is part of the Averda group company, was given the responsibility of managing city cleaning and waste collection. This company ruled the waste management sector for approximately two decades (Nuwayhid et al., 1996).

3. Waste Crises and Emergency Responses

1. Waste Crisis 1997: Emergency Response Plan 1997-2005

The year 1997 witnessed severe protests from civils against the outdated Amrousieh incinerator's harmful emissions as well as the dumping methods practiced at the Bourj Hammoud dump. This led the protestors to burn the incinerator in June of the same year as they accused the government of carelessness regarding health and environmental issues (World Bank, 2011). Based on the above, the Ministry of the Environment has set a 7-year emergency solid waste management plan (1997-2005) to be implemented by the CDR. Solid waste management contracts were issued to the private sector company Averda Group through its sister companies (Sukleen and Sukomi). The responsibilities included sweeping, collection, treatment, and disposal (CDR, 2006). The former services were performed by Sukleen whereas the latter which included sorting, baling, wrapping recycling, composting, and landfilling was attributed to Sukomi. The zone of coverage encompassed most of the Greater Beirut area (34 municipalities). Governorates besides Beirut and Mount Lebanon (800 municipalities) relied on local dumps. Bourj Hammoud dump was closed and a new sanitary landfill referred to as Naameh landfill was established. Supervision of tasks of Sukleen and Sukomi was handed to D.G. Jones and Laceco respectively. The major gap in the system was over-reliance on landfilling as the majority of the waste (80%) was being deposited. Also, alternating composting performance and minor levels of recycling, as well as a high net cost of $130/ton, was the case. As a direct consequence, the Naameh landfill has exceeded its original design capacity due to the incapability of the government to provide an alternative site and increase treatment capacities. Consequently, the contract with the mentioned private companies was being extended repetitively (CDR, 2015).

2. Waste Crisis 2015: Emergency Response Plan 2016–2020

Naameh landfill which was an emergency response against the Bourj Hammoud civil war dumpsite has become a bomb leading to a waste crisis year 2015. A secondary factor that worsened the situation was the mismanagement of private waste management contracts. Overreliance on the Naameh landfill has led to the extension of Averda's contract several times (Boswall, 2019). Initially, the landfill was intended to operate for ten years and receive a maximum amount of two million tons of waste. Yet, it stayed for eighteen years and held within its premises fourteen million tons of waste. The last six months' extension of the landfill's lifetime promised its closure on July 17, 2015. Meanwhile, CDR had to run public tenders to attract bidders for waste treatment in six operating areas. Potential landfill sites were identified in each zone. The tendering process was repeated for three rounds to conform with the validity requirements.

On the above-mentioned closure date, angry protestors blocked the site's entrance marking the beginning of a critical waste crisis. Furthermore, the council of ministers rejected the tenders' results one month later. As a result, all the waste services stopped leading to an eight-month crisis whereby mountains of waste sometimes reaching a height of 7 meters accumulated in proximity to neighborhoods. An estimated 20,000 tons of rotting waste were found in Beirut streets at the peak of the summer season. Three solutions were foreseen by the government for resolving the issue which are incinerating wastes, exporting wastes to Africa and Russia, and initiating two temporary landfills in Srar (North Lebanon) and Bekaa regions.

An emergency response plan was proposed and adopted by the Council of Ministers on March 12, 2016; nearly a year after the crisis. As a primary step, the companies responsible for waste treatment in Beirut and its suburbs were announced. Three short-term solutions were proposed:

- Reopening Naameh landfill for two months to get rid of the piled-up wastes over the last eight months and establishing two temporary landfills (lifetime of 4 years) in the Bourj Hammoud and Costa Brava regions located in Northern and Southern Beirut respectively.
- Reconsidering the energy recovery process as a shift from landfilling to incineration through the construction of waste-to-energy plants with a capacity of 2000 tons per day.
- Restressing the likelihood of municipalities managing their wastes using proper methods.

3. Landfilling aspects

Landfills are inevitable to integrated waste management because they provide the only terrestrial sink for hazardous substances that would otherwise be dispersed into the environment (Touze-Foltz et al., 2020). If operated sustainably, landfills may also represent a way to return materials and substances to the environment by applying material recovery (Powrie et al., 2014).

When designing a landfill, multiple technical factors which have a significant environmental impact should be considered such as location, liner systems, leachate collection, biogas control, and capping (USEPA, 2021; Al

Zaghrini et al., 2019; Katsumi et al, 2001). Dumpsites in Lebanon which include open dumping and open burning are a major threat to water resources and air quality and may pose significant health and carcinogenic risks (Nehme et al., 2021; Mouganie et al., 2020; Borjac et al., 2019; Khalil et al., 2018; Hilal et al., 2015). Moreover, large dumpsites or landfills for municipal solid waste that have been created and/or constructed adjacent to the seashore such as Tripoli, Bourj Hammoud, Costa Brava, and Saida pose a threat to seawater quality (Ecodit, 2015). Coastal landfills pollute water and sediments with microplastics (Kazour et al., 2019) and trace metals (Ghosn et al., 2020; Merhaby et al., 2018) which may reach biota and potentially harm marine organisms. They may be also linked with moderate coastal vulnerability (Ghousseina et al., 2018). Way before the 2015 waste crisis, landfills have already contributed by 5% to the coastal marine pollution of terrestrial origin (Shaban, 2008).

4. Lebanon's primary sanitary landfills

1. Naameh Sanitary Landfill

The CDR in consultation with the MoE and the sector implementation unit (SIU-3) adopted an emergency plan for MSW management in the Greater Beirut Area. The plan consisted of developing an integrated MSW management system that includes the following facilities:

- The Amrousieh and Karantina facilities for sorting and processing raw MSW
- The warehouse storage facility for sorting all bulky and recyclable materials
- The Naameh Landfill site for disposing of sorted MSW
- The Bsalim Landfill for disposing of inert and bulky materials

The emergency plan included collecting MSW from the Greater Beirut Area and transporting them to the Amrousieh and Karantina facilities. At these processing plants, the MSW was sorted into reject, recyclable, and compostable materials. The reject material was then compressed, wrapped, and baled for ultimate disposal at the Naameh Landfill site. Recyclable materials were separated and where possible sold. Compost was supplied to farmers without charge. Inert and bulky materials were transported to and ultimately disposed of at the Bsalim Landfill. The CDR commissioned Sukomi to develop and operate these facilities. To ensure proper development and operations, CDR retained LACECO as the consultant to provide technical assistance to the government through the supervision of the operator's activities at the site (Sweep-net, 2014).

The Naameh landfill site is situated in the Southern coastal zone of Lebanon, some 15 km south of Beirut and 4 km from the coastline at an average altitude of 250 m above sea level (Figure 1).

Figure 1. Map of the controlled landfills in Lebanon by the year 2021.

It started operation in October 1997 whereby it received baled waste rejects, a big fraction of putrescibles not sent to the composting plant due to its limited capacity, and finally the recyclable materials which were not recovered from the raw MSW. The original shelf-life of the landfill was 10 years with an expected capacity not exceeding 3 million tons of solid waste. However, the landfill underwent a series of extensions which lengthened its operation an additional 8 years where it held within its premises around 14 million tons of waste from the Greater Beirut Area. The landfill covers an area of 300,000 m^2. It is worth mentioning that the height of the waste ranged from 10 m at the lowest point to 100 m at some points making it one of the deepest landfills worldwide (El-Fadel et al., 2002).

Naameh landfill is considered one of the prime sanitary engineered landfills in the Middle Eastern area. The Naameh site was designed and managed within the guidelines and principles followed by established control and management of UK and European landfills. Golder Associates (UK)Ltd was appointed by Sukomi Landfill Projects to carry out the project management of the construction Quality Assurance during the construction of the landfill.

The ground profiles at Naameh underwent filling and re-compacting of the valley floor to allow the formation of a stable subgrade followed by a geotextile protection layer (500 g/m2). Above this layer comes the primary component referred to as geomembrane or Flexible Membrane Liner (FML) composed of HDPE (2.0 mm) material that is manufactured to a consistent standard with high manufacturing quality control at plants in either the USA or Germany. Each layout represents a panel, and adjacent panels were welded with purpose-designed machines by experienced installers. All liner construction work was fully supervised and subjected to certified quality auditor inspection, testing, and documentation. Above the FML additional protection layers of geocomposite, sand, and more geotextile (500 g/m2) were placed (Figure 2).

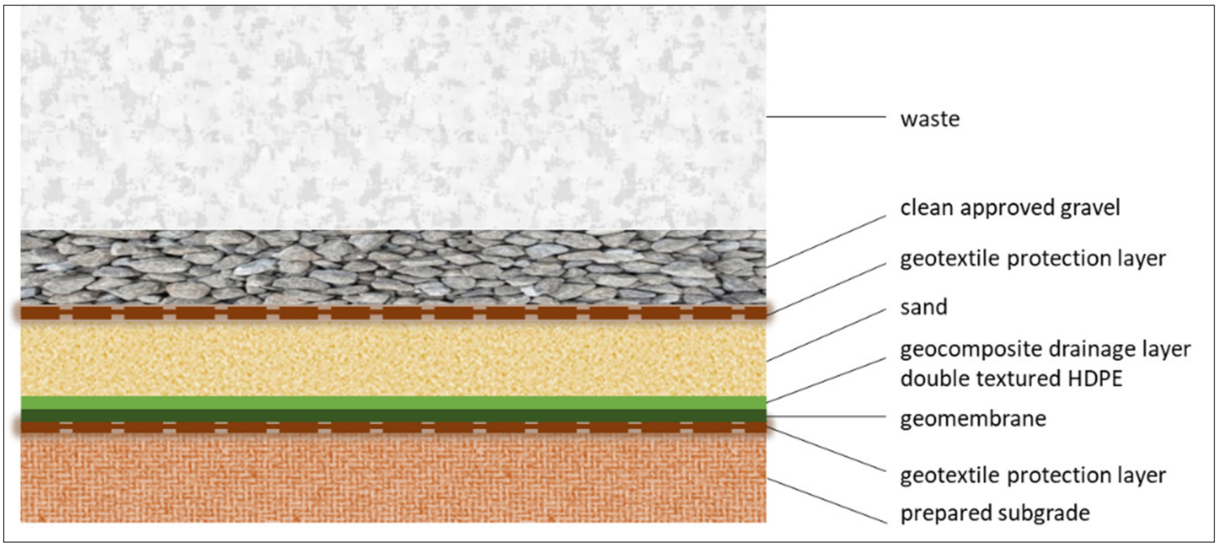

Figure 2. A diagram of the protective liner system in Naameh Landfill (Laceco, 2020).

Once in place, a drainage system was installed for the efficient removal of the leachate from the base of the landfill. It consists of a network of perforated pipes acting as preferential drainage pathways within a coarse aggregate blanket. The drainage system was brought to the lowest part of the relevant cell and connected to tubular leachate towers. Leachate was removed from these towers by periodic pumping to maintain leachate levels at a required minimum. The leachate is then taken to treatment and disposal. Therein, it passes through two stages of treatment: chemical and microbiological (sequential batch reactor).

During bale stacking, a pattern of gas wells was simultaneously constructed. Cells were interconnected by pipework. The collected gas went through the flaring system to prevent the discharge of methane gas into the environment and control odors about the volumes of gas processed (Figure 3).

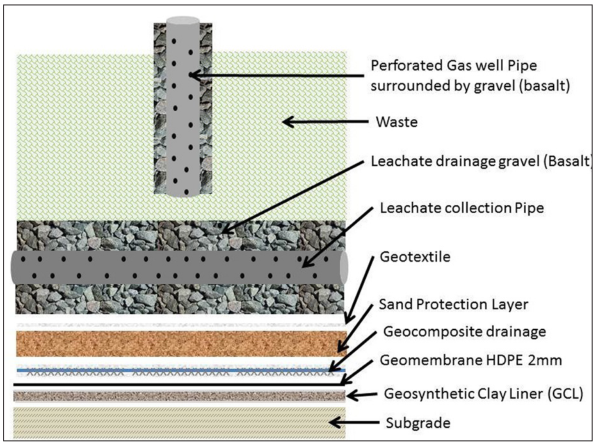

Figure 3. A diagram of the protective liner system with gas wells (Sawaya et. al, 2021).

At last, the landfill was subjected to closure via the construction of a special cap that shall prevent the ingress of rainwater into the wastes (Figure 4). After the closure of the Naameh landfill, two landfills were initiated to receive wastes from the Greater Beirut Area and are referred to as Costa Brava and Bourj Hammoud.

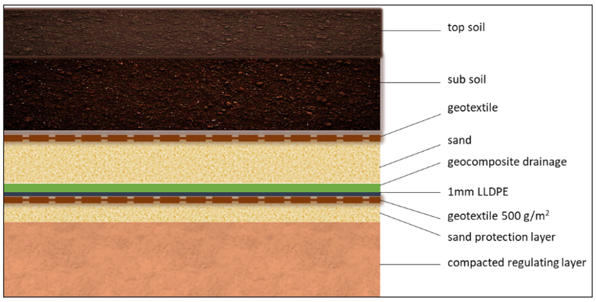

Figure 4. A diagram of the final capping system in Naameh Landfill (Laceco, 2020).

2. Zahle Sanitary Landfill

Zahle Sanitary Landfill is located in the Bekaa Valley in the Caza of Zahle. It receives waste from the City of Zahle and 18 neighboring municipalities. The World Bank funded its construction in 1998 so that it could handle 150 tons per day. This corresponds to eight percent of the waste generated in Lebanon (MoE/UNDP/ECODIT, 2011). In 2001, SERDIM with its partner SCS engineers was selected by the Municipality of Zahle, the CDR, and the World Bank to operate the landfill and to remediate Zahle's old dump site (Serdim Liban). Besides collecting about 180 tons of municipal waste, recyclable materials were being sorted by the private sector contracted at competitive prices. By 2013, 10% of incoming waste was being recycled (Chamieh et al., 2016).

The landfill was comprised of 3 independent disposal cells. The base of the cells was lined with a composite liner containing 60 cm of compacted clay covered by a 1mm HDPE geomembrane Leachate is removed by a series of 4 submersible pumps and relocated to a storage basin which is also equipped with a liner system. The leachate reaches the pumps by pipes fitted inside a sand and gravel layer and placed over the liner system. A modern LFG (landfill gas) extraction and destruction system was installed and operated. The system consists of wells installed in the waste connected to a piping system, a blower, and a flare.

SERDIM-SCS accepted, processed, sorted, and disposed of over 39,000 tons of waste. Each of the three initial cells was conFigured to be 14 m in height (from the cell bottom) with 4v:1h side slopes. After an assessment of the landfill's design, SERDIM-SCS combined the three cells into one large unit to increase the total capacity. Thus, the height was increased to 24 m and the side slope grades changed to 3v:1h doubling the capacity of the landfill.

Concerning the old dumpsite in the same area in Zahle, it has also been receiving waste from the Municipality of Zahle and other communities for the last 30 years. It occupied 15,000 m^2 and was over 25 m in height that it started to spill over adjacent properties. The waste was frequently burned to decrease its volume and only a small amount of cover soil had been applied over the years. The actual amount of waste disposed of at the old dump was eventually at least 225,000 m3. SERDIM-SCS removed them to one cell of the controlled landfill and returned the old dump site to its original ground elevation which became an open field ready for other uses.

The landfill receives five types of solid waste: household waste, retail waste, organic waste from parks and gardens, market waste, and demolition waste from households. The non-recyclable waste is either landfilled or composted. As the quality of the compost formed has not yet reached the commercial standard, it is currently used as a soil cover for the landfill. Leachate is collected and sent to Al-Ghadir's wastewater treatment station (south of Beirut) because the constructed leachate treatment plant is not yet operational. The treatment and disposal facilities of Zahle include several technical components: (1) a sorting and processing plant with an average capacity of 250 tons/day, (2) a composting plant with an average capacity of 90 tons/day, (3) a sanitary landfill, (4) a leachate treatment plant with a treatment capacity of 35m3/day, (5) a gas flaring unit with a maximum capacity of 300 Nm3 (normal cubic meter) per hour, and (6) a non-operational sorting and processing facility with an average capacity of 60 tons/day (Farah et al., 2019).

With increasing the recycling and composting capacities, the landfill's lifespan was increased from 17 years to 26 years and the costs of both its treatment and disposal operation and maintenance were reduced by two-thirds (World Bank, 2011).

3. Greater Beirut's alternative sanitary landfills

1. Costa Brava Landfill

The Costa Brava Landfill was opened in April 2016. It is one of the two landfills that have been suggested by the Lebanese government as a solution to the eight-month trash crisis that the country went through in 2015. It is located on the southern coast of Beirut, 167 meters away from the national airport (Rafic Hariri Airport). Al-Jihad Group for Commerce and Contracting (JCC) was contracted by CDR to construct and operate the landfill. In the process of landfill construction, JCC reclaimed 500,000 m^2 from the sea. This site receives around 1200 tons of sorted wastes from parts of Beirut and Choueifat areas as well as a small portion from other parts of Mount Lebanon cities. Further to the Beirut explosion on 4th August 2020, all the wastes entering the landfill were unsorted. The total amount of waste received until July 2021 is 2.5 million tons of waste.

Costa Brava landfill consists of 2 cells, 1 and 2 (2A and 2B), separated by 30 m by the Ghadir River. Cell 1 was divided into two phases (I and II). Phase I covered an area of 130,000 m2 and it stopped receiving the waste year 2018 whereby it held within its premises 1,200,000 tons of waste. This area was fully capped and another phase II as an extension to cell 1 is in the initiation and preparation phases for receiving around 780,000 tons of waste in a 78,480 m2 area (FFigure 5).

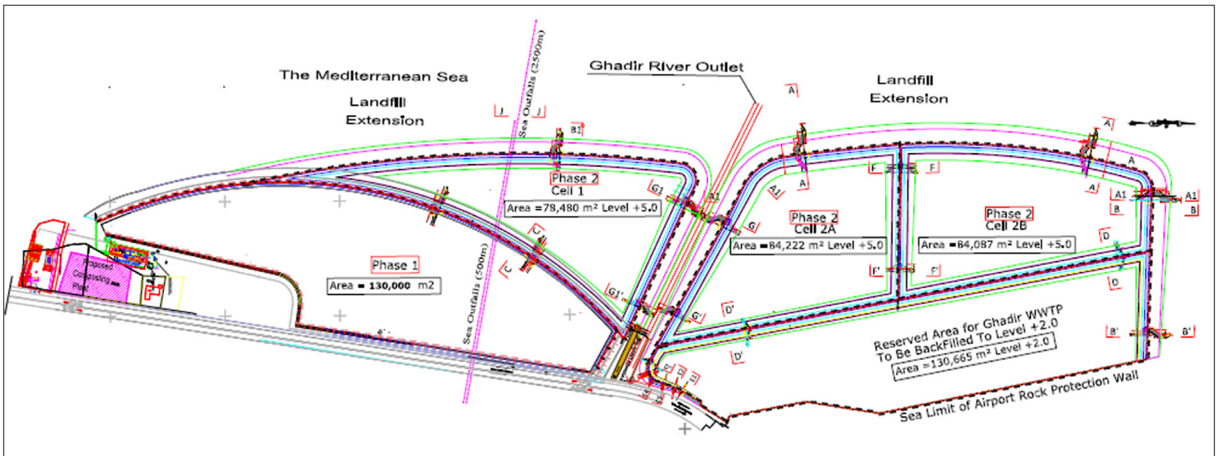

Figure 5. A diagram of the general layout of Costa Brava Landfill according to the phases, cells, and area (CDR, 2020).

The current cells (2A and 2B), which are presently receiving wastes, extend through areas of 84,222 $m^{2,}$ and 84,087 m2 respectively. They rise 16 m above sea level. The capacity of cell 1 is 1.3 mm3 and the capacity of cell 2 is 2.5 mm3 of which 1.75 mm3 tons are already occupied. In addition to the cells, there is a reserved area for a new Ghadir WWTP to be backfilled to level +2.0 spaced 130,665 m2.

The floor base of the landfill was initiated via compaction of the floor followed by a grading layer (15 cm), clay (60 cm), HDPE geomembrane layer (2.5 mm), geotextile (500 g/m2), sand (30 cm), and another geotextile layer then the wastes with a daily sand cover added above them (Figure 6). Only part of cell 1 was capped. The capping system consists of protective soil (25 cm), grading layer (15 cm), clay (50 cm), HDPE geomembrane (2.5 mm), sand (30 cm), agricultural soil (60 cm), and the final vegetative cover (FigureFigure 7).

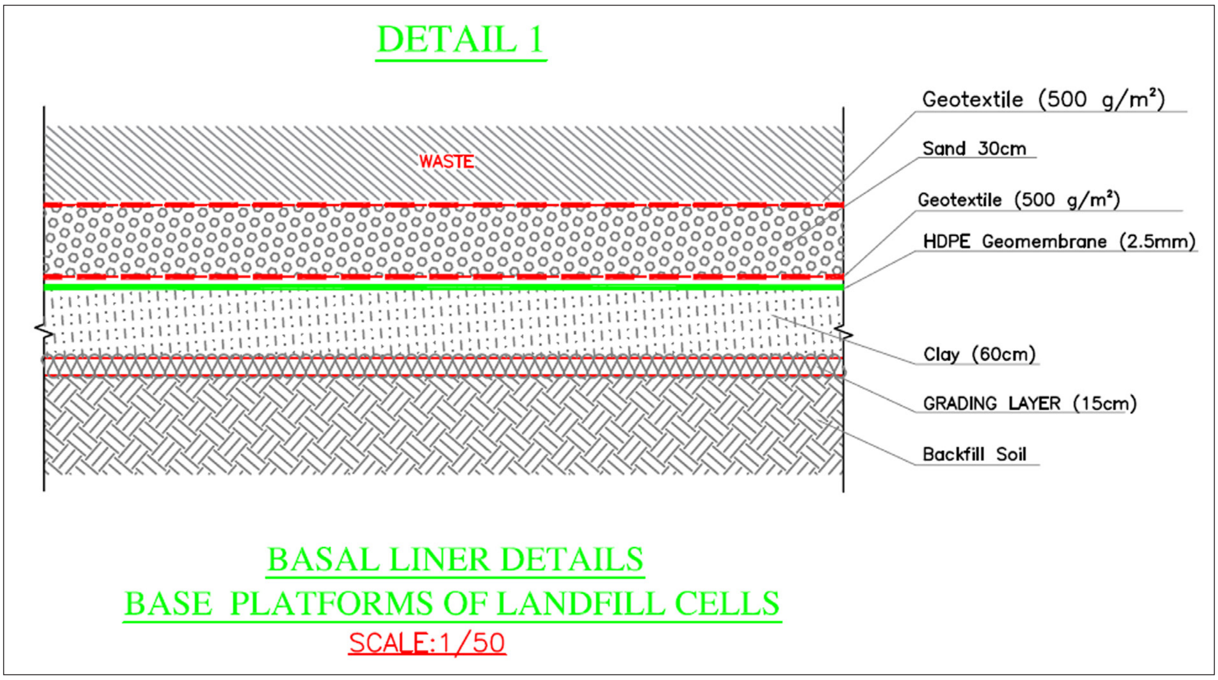

Figure 6. A diagram of the protective liner system in Costa Brava Landfill (CDR, 2020).

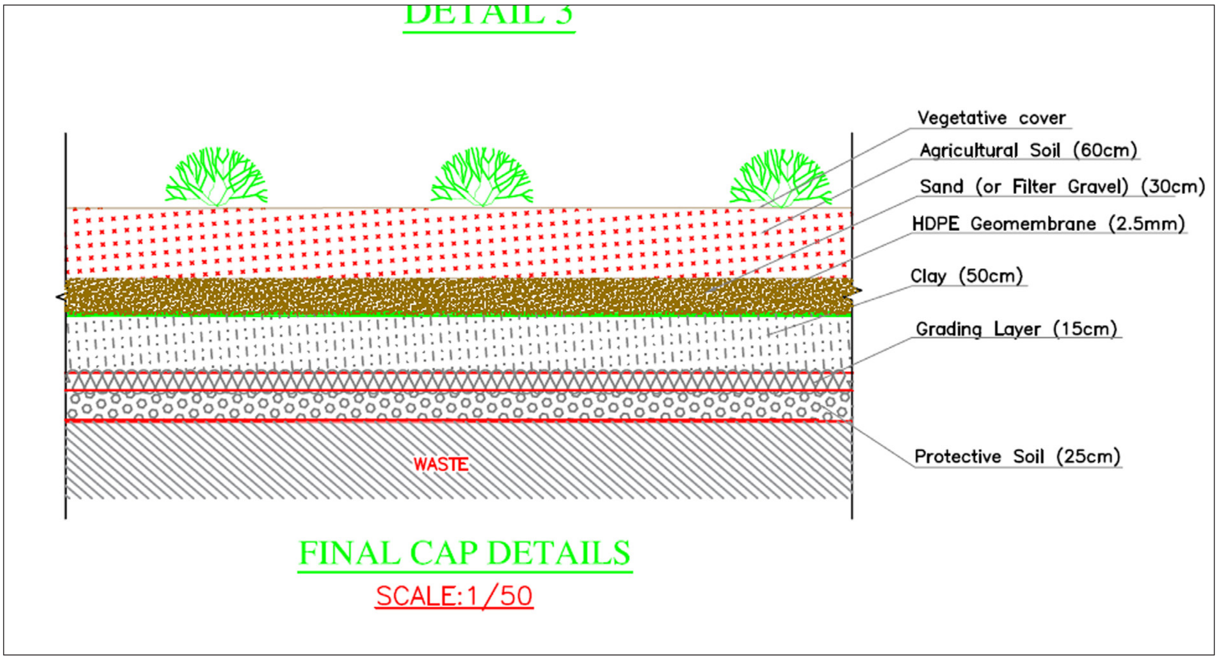

Figure 7. A diagram of the final capping system in Costa Brava Landfill (CDR, 2020).

Leachate resulting from the waste degradation process is gathered via a leachate collection system (200 Ø HDPE pipes, sump pits, leachate wells and submersible pumps) and further treated via two leachate treatment systems each about a phase. The leachate plant responsible for phase I was initiated by EMIT (an Italian company) in 2017 and offered three stages of treatment: physical/chemical, biological, and reverse osmosis (RO) system. The flow rate is 120 $m^{3/day.}$ Another treatment system initiated by Hofsteler (a Swiss company) encompassed leachate from phase II and consisted of physical/chemical, MBR, and RO systems for both the leachate and permeate. This system is currently nonfunctional due to the unavailability of sulfuric acid and its flow rate is around 120 m3/day. The water resulting from both treatments is being reused in dust control.

The biogas resulting from the waste degradation process is collected through a gas network and undergoes flaring at a combustion temperature of greater than 1000 degrees Celsius and a flow rate of 320-1600 m3/h. There are 63 gas wells in the landfill present (CDR, 2020).

Amidst the continual waste management crisis and absence of sustainable solutions, the landfill's life span was extended for an additional 4 years.

2. Bourj Hammoud–Jdeideh Landfill

Bourj Hammoud landfill is located on the northern coast of Beirut. It was fated to receive waste from the 1950s till 1990. Informal practices of open dumping especially on the coast prevailed during the years of civil and regional war (1975-1990). By the end of the war, tons of waste had accumulated by the Bourj Hammoud seashore. Nevertheless, the majority of the waste was dumped after the war, as the uncontrolled dump was declared an official landfill by a governmental decision. After the Civil War, the landfill received around 3,000 tons of waste daily. By 1997, the dump had far exceeded its capacity inevitably becoming an environmental and public health hazard. The situation led to a major protest by the inhabitants of Bourj Hammoud as the landfill was not only a dump site for the region, but also all the suburbs of Beirut and Mount Lebanon. Meanwhile, an incinerator in Amrousieh was supposed to back up the waste disposal process to Bourj Hammoud. However, this plan which was also government-based, failed as community protestors set the incinerator on fire. Eventually, the government closed the landfill on July 20, 1997, but without rehabilitation.

For years, Bourj Hammoud dumpsite released an estimated 120,000 tons of leachate annually equivalent to at least half the leachate produced by three main coastal dumpsites in Lebanon (Tripoli, Bourj Hammoud, and Normandy) (EU, 2006). However, LFG generation dropped rapidly to half its peak level only 4 years after landfill closure (El-Fadel et al., 2012).

As history repeats itself, after the solid waste crisis in 2015 and waste piling up on the streets, the government decided to rehabilitate the old Bourj Hammoud Landfill and open one next to it: the Jdeideh Landfill.

The Bourj Hammoud solid waste dump occupied a surface area of 163000 m^2 and rose to about 55 m above sea level with extremely steep side slopes. The waste, estimated at 6 million cubic meters, consists of demolition debris, excavation material, municipal solid waste, industrial waste, and hospital waste. Slope failure could occur at any time because the slopes are highly unstable and the underlying subsoil is a thick layer of soft clay which intensifies the stability problems. A consulting firm, Associated Consulting Engineers (ACE), was assigned to rehabilitate the old landfill (LINORD development project). The project had to solve the problems of soil instability, as well as leachate and gas generation, and aim at transforming the dump into a district park.

Bourj Hammoud garbage mountain was used as a backfill for the construction of these two new landfills. Hence, around 3.5 million cubic meters of waste, of which more than 50% were construction and demolition waste, while the rest were municipal waste, were excavated from the old dump and moved to the new nearby landfill, next to the fishing port. They were also used to reclaim land on the sea for building these new landfills and creating land for the municipalities.

The reason behind building two landfills instead of one is the area restrictions. The area between Bourj Hammoud Landfill and Jdeideh Landfill is 250 meters of seawater (Figure 8) which is the only passage of oil and gas pipes for the country. This zone is reserved for petroleum companies.

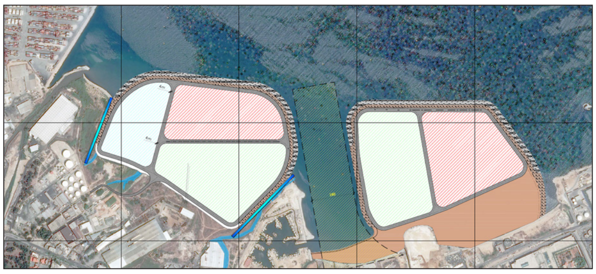

Figure 8. A map of Bourj Hammoud (left)-Jdeideh (right) Landfills general layout concerning the location and cells (CDR, 2020).

Bourj Hammoud landfill consists of 8 cells occupying 126,400 m^2 while the 11 cells of Jdeideh's landfill occupy 122,700 m2. It is noted that the Bourj Hammoud landfill reached full capacity, while 10 cells of the Jdeideh landfill are fully occupied and the 11th is now receiving waste. From the Bourj Hammoud landfill area, 97,400 m2 were reclaimed and given to the municipality while 119,500 m2 were reclaimed from Jdeideh as a public domain. Furthermore, around 65,000 m2 of the Bourj Hammoud landfill was kept to construct a wastewater treatment plant for Beirut.

Bourj Hammoud landfill closed in February 2019 and it has reached 20 m in height. It is noted that minimal leachate is being produced while biogas is still being emitted. Jdeideh landfill reached 15.5 m in height now.

The landfill land lies 0.5 m above sea level. First, 40-50 cm stabilized soil and then a protection and leveling layer (10 cm) were added. The landfill liner system consists of 3 layers: GCL (geosynthetic clay liner), which is composed of 2 layers of geotextile impregnated with bentonite, then 2 mm HDPE, and lastly geotextile 800 g/cm2. Finally, a drainage layer of 10-30 mm was added (Figure 9).

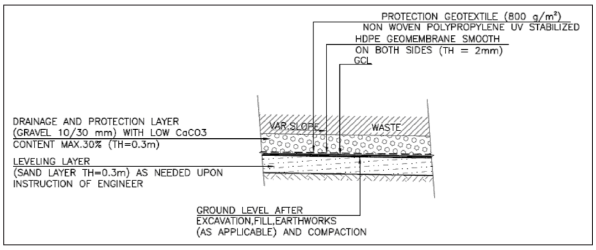

Figure 9. A diagram of the protective liner system in Bourj Hammoud-Jdeideh (CDR, 2020).

Capping consists of 5 layers (Figure 10). It starts with a leveling layer of sand around 0.3 m. Next, there are GCL, HDPE geomembrane textured at both sides (TH= 2 mm), protection geotextile (800 g/m^2) of non-woven polypropylene UV stabilized. Capping ends with a drainage and protection layer (gravel 10/30 mm) with low $CaCO_3$ with a content maximum of 30% (TH= 0.3 m).

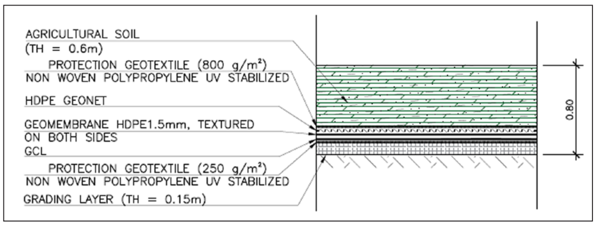

Figure 10. A diagram of the final capping system in Bourj Hammoud Landfill (CDR, 2020).

There are two leachate treatment plants, one for each landfill. Leachate circulates through corrugated 400mm diameter pipes (to allow aeration) and then reaches a leachate pond covered with grids to reduce evaporation and smell, after which they are pumped to a tank with blowers for aeration. Two leachate treatment plants include only reverse osmosis (RO) aided by a pH dosing pump (injection of sulfuric acid or caustic soda). The RO container plant for leachate treatment allows 120 m^3/d, has 3 stages, and a 69 bar max operating pressure of the leachate stage, with 85% yield and 5 m^3/hour recovery. It is worth mentioning that a gas flaring system was installed by an Italian company. However, the system did not operate due to the COVID-19 outbreak and the Beirut blast which prevented the operators from performing the necessary commissioning and training. Thus, the gas resulting from the landfilled wastes is being emitted into the atmosphere. Further to the Beirut explosion on 4th August 2020, all the wastes entering the landfill were unsorted. The total amount of waste received until July 2021 is 2 million tons of waste.

6. Other controlled landfills in Lebanon

1. Tripoli Landfill

Tripoli landfill is located alongside the coastline, adjacent to the Abou Ali River estuary, and north of the port of Tripoli. Its estimated area is 60,000 m^2. Tripoli Landfill receives around 450 tons of waste daily from the following cities: Tripoli, El-Bedawi, El-Mina, and El-Qalamon as well as from the north Palestinian refugee camps. Its operation was initiated year 1980 and it was converted to a semi-controlled dump year 2000 (Halwani et al., 2020). The dump's operation was supposed to end the year 2012, however, it is still receiving waste until present without any regard for the associated ecological risks (Halwani et al., 2014).

To contain the open dump and prevent its expansion into the Mediterranean Sea, a peripheral seaside wall was constructed the year 1997. Furthermore, the Union of Al-Fayhaa Municipalities (UFA) initiated a project year 1999 which consisted of shifting the site's operation to that of a controlled landfill through its rehabilitation. Thus, the contractor (BATCO) was assigned by CDR to manage the controlled dump. It enhanced the waste disposal modes via the incorporation of gas extraction wells and flaring units (CDR, 2002).

Tripoli landfill's operation ranged from waste placement, application of daily cover, compaction, and biogas flaring to leachate control (both stopped in 2013) (Halwani et al., 2020).

The landfill holds 1.1 million m3 of waste. with a height of 45 meters (UFA, 2018). The landfilling operation is a simple one consisting of spreading and compacting the waste in layers of approximately 50 cm and then covering it with 15 cm of inert soil material.

The landfill's leachate was drained into pits and it underwent a partial treatment process from years 2009 until 2013. The leachate was subjected to a recirculation procedure whereby it was sprayed and evaporated on the compacted solid waste and then recollected via a peripheral network underneath the waste. However, the continuous increase in the height of the solid waste as well as the construction of the peripheral trenches exposed the system to a great risk as the associated equipment (pumps, etc.) couldn't sustain the variations. The leachate treatment process consisted of an aerobic digester with nitrification and anoxic denitrification; clarification; chlorination; and filtration (sand and carbon filter). However, the efficiency of the treatment was altered due to the increase in the volume and height of solid waste as well as the rainwater ingress which overwhelmed the design capacity of the plant (36 m3/day). Therefore, a fraction of the leachate was recirculated in the landfill and another one was released into the river discharging into the sea (Halwani et al., 2020).

As a replacement for the old flare (500 m3/h), a new one with a higher capacity (1100 m3/h) was installed year 2009. However, the system stopped in 2013 as the height of waste exceeded 32 m and thus the need to elevate the gas wells vertically. Therefore, the biogas released is not being treated and might cause an accidental huge fire which in turn will lead to serious health and environmental impacts (Halwani et al., 2020; Halwani et al., 2017).

OMSAR, with financial support from the European Union, has constructed a sorting and composting plant near the dumpsite area with a capacity of 420 tons/day. However, the plants were stopped just a few weeks later due to complaints from residents about the awful odors detected in the city, low recycling efficiency (less than 5%), and poor compost quality. Those shortfalls resulted from troubleshooting the biofilter and maturation phase of the compost. To solve this issue, technical modifications for the facilities are being looked upon by OMSAR and UFA. The waste entering the landfill is not being sorted except by scavengers who were allowed by UFA to collect recyclables before spreading the waste in the dump.

As the landfill succeeded in reducing the amount of waste disposed from 420 tons/year to 350 tons/year, an extension into a new temporary landfill was performed by reclaiming 60,000 m2. The new landfill started its operation in February 2019. It consists of three cells and the design capacity is for three years. Further to its closure, the rehabilitation process will be initiated (Halwani et al., 2020).

2. Saida Dump

Saida dump was established year 2004. It is located on the seafront, at a distance of 200 meters from commercial units and nearby houses (Farah et al., 2019). The dumpsite is being managed by the municipality of Saida. It receives around 300 tons of waste daily from 15 municipalities. Since its establishment year 1982, it received all kinds of waste

(60% rubble and 40% municipal waste) which piled up to form a waste mountain reaching a height of 55 meters (MoE/UNDP/ECODIT, 2011). It covered an area of 60,000 m^2 and held waste at an estimated volume of 1.2 million m3 which rendered it an enduring eyesore to tourists and residents (Farah et al., 2019; ILO/UNDP, 2011). Thus, countless complaints from residents and fishermen were raised as a result of the severe environmental repercussions with the accompanying adverse impacts on health (UNDP, 2013).

With support from the UNDP as well as the Prince Walid Bin Talal Humanitarian Foundation, the dumpsite was transformed into an enclosed landfill via a mining procedure that allowed for the treatment of waste at the dumpsite (UNDP, 2017). Part of the land was reclaimed for wastewater treatment and gas emanations and another part (33,000 m2) was transformed into a park year 2016. IBC (a private waste contractor) constructed a mechanical and biological treatment plant at a distance of 200 m. An anaerobic digester started its operation in 2013 south of the dumpsite (MoE/UNDP/ECODIT, 2011).

The treatment plant received 500–600 tons of waste daily from areas within and outside the district. Further to sorting, the waste is treated via anaerobic digestion and then processed to generate electricity. Putrescibles are packaged as organic fertilizers, plastics are recycled, and refuse-derived fuel is sent to cement plants (Farah et al., 2019).

The closure of the Naameh landfill year 2015 and the temporary closure of a waste-to-energy facility in Bekaa which received IBC's residual waste after treatment has led to the accumulation of waste at the Saida site. Thus, the quantities of waste received since 2015 have by far surpassed the treatment plant's capacity. Subsequently, IBC got rid of the residuals via shredding with gravel followed by dumping in a nearby sea site enclosed by a breakwater. As a result of the rising local pressure, IBC was obliged to restrict the waste received to Saida and Zahrani districts solely as of the year 2018.

7. Discussion

On an annual and seasonal scale, statistically insignificant increasing and decreasing trends in rainfall are found in the three rain gauging stations that were studied. The rainfall patterns in the three AERs WL3, IL1a, and DL1f have changed differently in each season and annually. These changes show that climate change has influenced the rainfall trends and hence some impacts are faced by the agriculture and aquaculture sector in the country due to these trend changes, even though those are statistically insignificant. In the examined rain gauges, no significant increase or decrease in rainfall was found.

Except for the landfills in Zahle and Naameh, which are located in the interior, all of Lebanon's major landfills are located on the coast: the Costa Brava dump, the Saida sanitary landfill, the Bourj Hammoud landfill, and the Tripoli landfill. The city's landfill is a significant and dangerous part at the same time. If a landfill does not adhere to sanitary landfill regulations, the pollution it causes harms the surrounding areas, particularly the residential areas, when designing an urban metropolis. When choosing a landfill site, it is crucial to maintain a safe and healthy environment because waste pollution threatens the ecosystem and consequently human health and well-being (Halwani et al., 2020).

According to a study done by Amkieh in the year 2021, the residential area of Bourj Hammoud is mostly affected by the landfill because of its proximity to the area and the high-risk weather during the summer. This area is also the most polluted, along with the landfill site in Tripoli City, as the results show that it has the same level of pollution. The climatic circumstances (such as warmth and humidity) are worse in the coastal zone in the summer than in the inward area, which increases the pollution by landfills that influence the nearby zones, and as a result, the pollution degree is higher in the coastal region than the inward area.

The landfilling disposal approach may have several negative effects due to unplanned landfill area development that may lack proper engineering controls or even result in insufficient oversaturation. This could cause leachate to form, which could then escape containment and seep into the groundwater. Therefore, for both engineered and uncontrolled landfill sites, the migration of landfill leachate into groundwater poses a major environmental danger (Baghanam et al., 2020). Even in hygienic engineered landfills with related geomembrane layers, the environmental impact of landfill leakage was repeatedly found. Therefore, it is crucial to evaluate any risk of groundwater pollution brought on by landfill operations (Sawaya et al., 2021; Kanj et al., 2022; Nehme et al., 2020; Nehme et al., 2019; Haydar et al., 2022).

Plans for managing solid waste are typically successfully implemented in industrialized nations, where each has a special strategy that works with its metropolitan infrastructure. Solid waste has long been a problem in Lebanon, but it has become much worse recently in various parts of the country, with differing effects on the environment and the health of the population. There are several factors contributing to this increase, one of which is the populace's consumption-based way of life and lack of awareness of personal responsibility.

The future of MSW management in Lebanon will not be brighter unless the implementation of an effective solid waste management framework is adopted. This will aid in preventing the oversaturation of landfills and the emergence of uncontrolled dumpsites.

The drafted law on integrated solid waste management (law 80) is the solution for the improvement of the system. This law was approved year 2018 and is still awaiting implementation The law is characterized by three basic principles which are: the establishment of the legal framework for solid waste management, sound management of solid wastes through waste minimization practices (sorting at source, recycling, energy recovery), and applying the polluter pays principle and prevention of open dumping. Thus, for the implementation of this law, it is of crucial importance to set and issue application decrees as well as strategies and plans that are missing to obtain an integrated

SWM system in Lebanon. Additionally, the rising economic crisis further aggravated the situation as it hindered the operations of ministries due to the scarce resources and lack of personnel to follow up on the law implementation.

8. Conclusions and Recommendations

Throughout the years there was no adoption of any comprehensive and sustainable solid waste management strategy by the government which aims at solving the continuously occurring waste management crisis. Thus, overreliance on landfills through their expansion is considered a temporary solution that will reach an end sooner or later given the restricted spaces in Lebanon. The Naameh landfill was expected to operate for ten years, but its lifetime was extended to an additional 8 years. History is repeating itself with both Costa Brava and Bourj Hammoud landfills which are being expanded to receive additional waste in the absence of alternative solutions. It can be said that the lack of human resources as well as suitable facilities, corruption, and inefficient technical skills have led to this extensive failure in municipal solid waste management. Hence, the lack of environmental legislation in itself is not the center of the problem but rather the absence of law enforcement and/or the availability of other alternatives. With the absence of sustainable waste management solutions, unsorted wastes will continue entering landfills leading to shortening their lifespan and their overexploitation. This will in turn lead to other waste crises whereby wastes will accumulate on the streets causing adverse environmental effects with associated pollution problems.

Thus, the country requires for the upcoming future, a sustainable development strategy with waste management (minimization, reuse, and recycling) among its main priorities. The key to a sustainable solid waste management system requires an elevated degree of public participation, effective legislation, ample funds, and modern waste management technologies. Improvement of the waste management scenario can be achieved by the implementation of source segregation, encouraging private sector participation via awareness campaigns, availing recycling and waste-to-energy systems, and developing a strong legislative and institutional framework.

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