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Review

The Factors Influencing the Landfill Leachate Plume Contaminants in Soils, Surface and Groundwater and Associated Health Risks: A Geophysical and Geochemical View

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Abstract: Understanding the factors influencing the impacts of landfill leachate plume (LLP) contaminants in soils, surfaces, and groundwater systems is essential in combating landfills' environmental impacts. Previous studies have concentrated on the environmental effects of LLPs, ignoring the influencing factors fueling the impacts. This review explores the factors influencing the migration and distribution of leachate plume contaminants, which inversely exacerbate their venoms on environmental and public health. Some selected leachate plume influencing factors were examined from geophysical and geochemical perspectives. The geophysical view provides valuable information on subsurface influential factors such as the hydraulic properties, geological composition, and the presence of preferential flow pathways that can influence the spread of contaminants. From the compiled studies, these influencing factors of LLPs remain critical consideration when siting bores/wells and landfills. In addition, the geochemical processes such as adsorption, desorption, precipitation, contaminant properties, and microbial transformations influence the fate and transport of LLP contaminants in soils, surface water sources, and groundwater were discussed. The interactions between LLP contaminants and soil, water, organic matter, and microbial communities determine the overall well-being of the environment. Understanding these geochemical and geophysical processes is essential for predicting the long-term behaviour of contaminants and designing effective management strategies. Based on the compiled studies, geophysical regularization requires that drinking water sources should be sited at least 100m away from the landfill to at least 15m depth, while a standard landfill should be located in a zone with deep aquifers. In conclusion, the Integration of geophysical and geochemical approaches provides a comprehensive understanding of the complex interactions between LLP contaminants and the environment, which enables researchers and environmental stakeholders to assess the risks associated with contaminant migration, develop roadmap monitoring programs, and implement sustainable management techniques to protect soil, surface/groundwater resources, and public health from the impacts of LLP contaminants.

Keywords: landfill leachate plume, geochemical, geophysical, environmental vital organs, influencing factors, public health

1. Introduction

Understanding the environmental implications of landfill leachate plumes (LLPs) and waste management challenges, especially in developing nations, is quite essential for environmental health and sustainability. Landfills are an essential part of waste management infrastructure, serving as repositories for the disposal of industrial waste, agricultural waste, municipal solid waste (MSW), and other forms of refuse. However, the decomposition of organic matter and the interaction of various waste materials within landfills can lead to the generation of a complex and potentially hazardous liquid known as leachate plumes [1,2]. Landfill leachate is a contaminated liquid that percolates through the waste with significant environmental and public health risks if not well-managed. One of the key challenges associated with landfill leachate is the formation of leachate plumes [3–5], which can have far-reaching implications for ecosystem health, surface and groundwater quality, and human well-being. LLPs are characterized by the migration of contaminated liquid through the subsurface environment, driven by the force of gravity and the hydraulic conductivity of the surrounding soil and rock formations [6]. As leachate percolates through the waste mass, it dissolves and mobilizes a wide range of contaminants, including organic compounds, pathogens, ammonia, heavy metals, and other forms of pollutants [7,8]. These contaminants originate from different sources such as decomposing organic matter, industrial waste, and household chemicals within the landfill, making LLPs a complex and dynamic mixture of pollutants.

The transport of leachate plumes through the surface and subsurface environment is usually influenced by a variety of factors, including the porosity and permeability of the soil and rock formations, the presence of preferential flow pathways, and the hydraulic gradient [9,10]. As a result, leachate plumes can migrate over significant distances from the source landfill, potentially compromising the soil integrity, groundwater quality, body of surface water purity, and sensitive ecological receptors. The persistence of leachate plumes is another key characteristic that has received the attention of researchers across the globe. Due to the slow degradation of many contaminants and the long-term release of pollutants from the landfill, leachate plumes can persist in the environment for extended periods, posing ongoing risks to environmental and human health [11,12]. The migration of LLPs can have a range of adverse environmental implications, especially on groundwater and surface water quality. Studies have shown that one major challenge of groundwater contaminants is that it is difficult to recover them once it is contaminated [13,14]. Therefore, groundwater contamination remains a significant concern in groundwater resource management because the leachate plumes infiltrating the aquifers can lead to potential risks to human health and ecosystem integrity. The presence of organic compounds, heavy metals, and other contaminants in leachate plumes can also have toxic effects on aquatic organisms, disrupting food webs and impairing the ecological balance of surface water [15].

In addition, groundwater and surface water contamination due to LLPs can pose risks to soil quality and vegetation health [16]. This is because the infiltration of contaminants into the soil can impair its fertility and structure [9], which potentially affects the growth of plants and agricultural productivity in the vicinity of the landfill. However, the management of LLPs presents a range of technical, regulatory, and financial challenges. One of the primary difficulties encountered in the leachate plume characterization and monitoring is the complex composition and dynamic behaviour [17], which makes it more challenging to predict their migration pathways and assess their environmental impact accurately. Therefore, effective monitoring and assessment strategies are essential for understanding the extent of contamination, identifying potential receptors at risk, and evaluating the effectiveness of remediation measures. Furthermore, the release of nutrients such as ammonia and phosphorus from leachate plumes can contribute to eutrophication in surface water bodies, leading to algal blooms, oxygen depletion, and the degradation of water quality [4,18]. The cumulative impact of leachate plumes on the environment can be substantial, affecting the ecological functions of aquatic ecosystems and compromising the availability of clean water resources [19–21]. This book chapter provides a comprehensive overview of LLPs, including their characteristics, environmental impact, and the challenges associated with their management. By understanding the nature of leachate plumes and the potential risks they pose, stakeholders can develop effective strategies to mitigate their impact and protect the environment and public health.

2. Landfill Leachate Plumes and the Influencing Factors

The LLPs contain a wide range of contaminants with diverse properties, such as organic compounds, which contain a variety of organic compounds, including volatile organic compounds (VOCs) like benzene, toluene, ethylbenzene, xylene (BTEX), polycyclic aromatic hydrocarbons (PAHs) and chlorinated solvents [22]. These organic compounds can exhibit varying levels of persistence, mobility, and toxicity [23], posing risks to environmental and human health. In addition, the landfill leachate may also contain heavy metals (HMs) such as lead, iron, cadmium, zinc, chromium, mercury, and arsenic, which can persist in the environment and bioaccumulate in living organisms. Several properties of HMs such as solubility and reactivity, potentially have long-term environmental impacts [24], which are important considerations in assessing the risks associated with leachate contamination. The mobility and bioavailability of heavy metals are determined by their solubility in water. Highly soluble metals can readily permeate both surface and groundwater, posing a threat to aquatic ecosystems and sources of potable water [25]. Typically, plants acquire soluble heavy metals via soil interactions and incorporate them into the food chain, which potentially affects human health [26]. Reactive heavy metals, on the other hand, can combine with other elements to generate compounds that might be more hazardous than the metals alone. Mercury, for instance, can combine with organic materials to create the extremely hazardous molecule methyl-mercury [27]. Therefore, adequate knowledge of these characteristics facilitates the creation of efficient plans for controlling, reducing, and observing the effects of heavy metals on the environment.

Landfill leachate can be rich in nutrients such as ammonia, nitrate, and phosphorus, which can contribute to eutrophication in surface water bodies [4]. The properties of these nutrients, including their potential for promoting algal growth and causing oxygen depletion, are important factors in understanding the impact of leachate on aquatic ecosystems. Moreover, LLP may also contain pathogenic microorganisms such as bacteria, viruses, and parasites, which can pose risks to human health and ecosystem integrity [28]. The properties of pathogens, including their survival and transport in the environment, are critical in assessing the potential health hazards associated with leachate contamination [29]. The properties of LLP are not limited to the aforementioned, it may also contain acidic and alkaline (pH), salinity and conductivity, persistence and degradation, mobility and transport. In conclusion, the properties of contaminants in leachate are diverse and complex, requiring careful consideration in the assessment, monitoring, and management of leachate plumes to mitigate their environmental impact and protect human health. Figure 1 provides a graphical illustration of LLPs impacts on environmental vital organs such as public health, air pollution, surface water sources, groundwater, soil, and vegetation alongside some influencing factors. Therefore, understanding the factors influencing the LLP contaminants in soils, surface and groundwater is crucial for assessing the potential impact of leachate plumes on the environment and human health, as well as for developing effective strategies to manage and mitigate their migration.

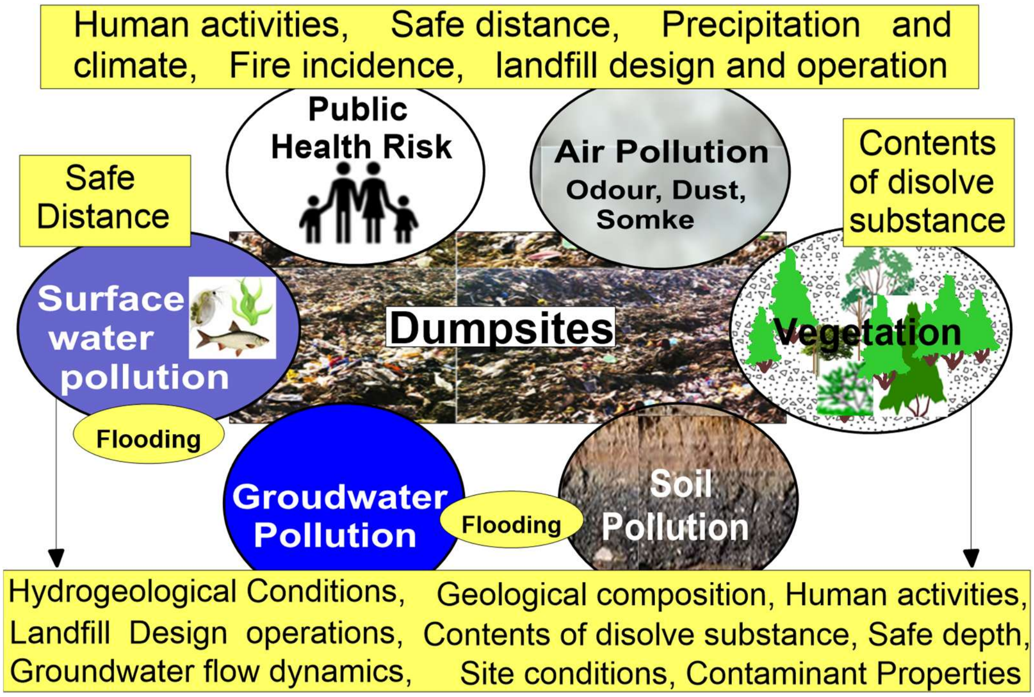

Figure 1. Impacts of Landfill Leachate Plume Contaminants and Factors Influencing it.

3. The Scope of the Study

This study focuses on assessing factors influencing the LLP within soils, surface water sources, and groundwater from geochemical and geophysical views. However, the scope of this study is not limited to geochemical and geophysical views because there are several other factors controlling the degree of impact of LLPs on the environment from other views such as engineering, especially landfill design and operation. This study examined the contaminant properties, contents of a dissolved substance, site-specific conditions, topography, flooding, safe distance and depth, geological, composition, hydrogeological conditions, groundwater flow dynamics, precipitation and climate, the landfill terrain and topography, and human activities. The scope of the study involving the influence of LLPs from geophysical and geochemical perspectives is broad and multidisciplinary. It encompasses the investigation of the movement, behaviour, and impact of LLPs on the surrounding environment, including soil, groundwater, and surface water. The study may involve the following aspects:

a. Geophysical Surveys: Utilizing geophysical methods such as electrical resistivity, ground-penetrating radar, and seismic surveys to characterize the subsurface properties and detect the presence and movement of LLPs. These surveys can provide valuable information on the spatial extent, depth, and flow patterns of the plumes.

b. Geochemical Analysis: Conducting geochemical analysis of soil and water samples to identify the composition of landfill leachate and its potential contaminants. This may involve analyzing parameters such as pH, conductivity, heavy metal concentrations, organic pollutants, and other chemical constituents to assess the impact of leachate on the surrounding environment.
c. Hydrogeological Modeling: Developing numerical models to simulate the transport and fate of LLPs in the subsurface. This may include assessing the potential migration pathways, dispersion patterns, and the long-term behaviour of leachate plumes under different hydrogeological conditions.
d. Environmental Impact Assessment: Evaluating the potential ecological and human health risks associated with LLPs, including the contamination of groundwater resources, surface water bodies, and the accumulation of pollutants in the soil and biota.
e. Remediation Strategies: Investigating the effectiveness of various remediation techniques for mitigating the impact of LLPs, such as groundwater extraction and treatment, in-situ bioremediation, and barrier systems.
f. In summary, the scope of study involving the influence of LLPs from geophysical and geochemical perspectives aims to provide a comprehensive understanding of the behaviour and impact of leachate on the surrounding environment, as well as to develop effective management and remediation strategies to protect human health and the environment.

3.1. Precipitation and Climate

Precipitation patterns and climate conditions can affect the movement of leachate plumes by influencing groundwater flow and recharge rates. The events of heavy rainfall, especially in tropical regions, can lead to increased leachate generation and the potential for plume expansion [6], while drought conditions may impact the dilution and dispersion of contaminants. The regional climate event should be studied and understood for proper management of waste materials. In most tropical regions of the world, where annual rainfall alternates between 1000–2000 mm and the temperatures vary between 10 °C and 40 °C, landfill management is usually difficult to manage [6]. On the other hand, the evidence is clear that the Earth is getting warmer and warmer, which is largely triggered by anthropogenic activity. As a result, the event of extreme weather phenomena, have devastating consequences for humankind and ecosystems. According to remarkable research, leachate pollution varies greatly between climatic zones [6]. Leachate pollution concentrations in tropical countries are substantially greater than in the polar zones, particularly for biological and chemical oxygen demand (COD and BOD) values [9].

Rain events have significant implications on landfills, especially when rainwater penetrates the waste materials heaped on open landfill sites. When water infiltrates

MSW within the landfill, it interacts with organic and inorganic materials, which form leachate plumes with highly toxic chemicals [30]. These toxic chemicals have significant implications for groundwater systems when they leach into the ground soil. Studies have shown that about two-thirds of waste materials in landfills contain biodegradable organic matter, which decomposes easily to produce methane gas. When this methane gas is mixed with air surrounding dumpsite/landfill sites, it creates unpleasant odours due to decaying organic waste [10,31]. This development in landfill can lead to the loss of biodiversity approximately 30 to 300 species per hectare [13]. Also, the decaying organic material and the mixture of toxic substances can impact the quality of soil around landfill sites, which can alter local vegetation and permanently affect soil fertility [32]. As a result of these challenges, open landfill sites are often unpopular and unpleasant to residents due to their smell nature, appearance, and associated health risks [6]. In summary, rainwater or rain events in unsanitary landfills exacerbate the environmental threats posed by landfills, which affects the groundwater systems, biodiversity, air quality, and soil. Recent studies show that rain events influence the contents of biochemical and chemical oxidations within the landfill, which inversely determines the solid waste decomposition rate within dumpsites.

Rainwater is a significant influencing factor affecting LLPs in terms of quantity and quality, which is usually measured in the dilution effect, contamination pathways, and long-term implications. For instance, during heavy rainfall, the volume of LLP increases as a result of rainwater infiltration into the landfill, which dilutes the concentration of pollutant elements such as electrical conductivity, pH, HMs and biogeochemistry in the leachate plumes. Inversely, during dry periods, leachate plumes become more concentrated as less rainwater infiltrates the waste layers [33]. In addition, rainwater carries dissolved and suspended contaminants from the landfill surface downward through the waste layers to groundwater units [34]. These contaminants can seep through pathways into the soil, potentially affecting its fertility and quality, and subsequently spreading down to the surface water sources and regional groundwater [35]. Furthermore, the long-term implications of these activities cannot be overemphasized because as long as the event rainwater continues to interact with residual waste, generating leachate plumes for many years even after the closure of the landfill [10]. Proper waste management and monitoring are quite essential to prevent long-term contamination of water resources [36]. This study is quite essential because it provides adequate knowledge about the planet Earth that sustains the existence of humankind to next generations.

3.2. Terrain and Topography of Landfill Site

The behaviour and environmental effects of leachate plumes are significantly influenced by the topography and geography of a landfill site. Some of the major factors of topography and terrain of landfill sites that influence the mobility and distribution of LLPs include (i) gradient and slope, (ii) surface water interaction, and (iii) dilution and recharge. The direction of the flow of leachate plumes and velocity can be significantly influenced by the land's inherent slope [9]. Although steeper slopes may cause surface runoff to accelerate and decrease penetration, they may also cause leachate to disperse over a greater area [1]. Leachate plumes have a greater tendency to contaminate groundwater in locations where the water table is near the surface [37]. Leachate can leak downhill and spread laterally in areas of terrain where water collects or forms mounds at the water table1. In addition, the rate at which leachate penetrates into the earth is dependent on the nature of the soil and its permeability. High permeability sandy or gravelly soils facilitate faster leachate migration, but low permeability clayey soils slow down the process [14]. The spreading of leachate as a result of changes in groundwater flow velocity is influenced by topography. This may result in a greater dispersion of pollutants [1,38]. Although soil that receives substantial rainfall can dilute leachate concentrations, it can also increase the amount of leachate produced. This may result in pollutant plumes that are more widespread and concentrated [6]. On the other hand, if the topography pushes runoff in the direction of nearby surface water bodies, there may be a chance that leachate from the landfill will seep into these bodies of water. This may cause lakes, streams, and rivers to become contaminated [10]. Therefore, for the purpose of minimizing environmental impact, landfill management strategies must be designed with an understanding of these factors.

3.3. Contaminant Properties

Contaminant properties depend on several factors such as the age of the landfill, leachate plume quality, and degree of HM concentration, which can affect LLP movement significantly. The quality of LLP is usually assessed based on parameters like total dissolved solids (TDS), biological oxygen demand (BOD), chemical oxygen demand (COD), and total Kjeldahl nitrogen. For instance, a study observed that the ratio of BOD/COD in leachate plumes shows the rate of biodegradable waste within the landfills. This implies that the rate at which the waste materials stack at the dumpsites or landfills decomposes accelerates during rainstorm events, which in turn affects the leachate's pollutant content. A recent study estimated the BOD/COD of five dumpsites with 0.529, 0.531, 0.546, 0.507, 0.577, and 0.575, indicating moderate rainwater content within the dumpsites. According to Kalčíková et al. [39] and Hoai et al. [40], a high BOD/COD ratio indicates that organic matter is more easily biodegradable, which eventually enhances the spread of leachate plume distributions. Inversely, a low BOD/BOD suggests that a significant amount of organic matter in the water is not readily biodegradable, which can have a detrimental effect on the integrity of the water and cause oxygen depletion in aquatic ecosystems [39,40]. Furthermore, the total ratio of BOD to COD provides insight into analyzing the overall health status of water bodies, while estimating the success of wastewater treatment operations and guiding judgments on adequate treatment strategies to maintain the quality of water.

These emerging pollutants in LLPs are still not well-studied in tropical regions [41,42]. The age of landfills also plays an important role in LLP because the young leachates usually contain volatile fatty acids, which decrease with time [36]. In addition, microbial activities such as methanogenic/sulfate-reducing bacteria, manganese/nitrate-reducing, and iron-reducing around landfills, mostly attenuate within the first 50 meters from the landfill [43]. For instance, in Norman, Oklahoma, USA, a study shows the elevated concentrations of nonvolatile dissolved organic carbon, chloride, iron, methane, ammonium, and bicarbonate in a landfill leachate plume [44].

For instance, HMs such as cadmium, iron, copper, chromium, zinc and lead and organic compounds such as benzene or chlorinated solvents can have different migration rates and persistence in groundwater systems [34], which implies that contaminants with higher solubility tend to spread more rapidly through the subsurface, potentially creating larger plumes. LLP Contaminants can exhibit varying degrees of mobility. This implies that some may readily adsorb onto soil particles or organic matter, while others may dissolve in water and move with the flow [10], which controls the rate at which LLP pollutants flow into the environment. Less sorptive ones can travel farther, while highly sorptive contaminants may remain near the source [1]. Therefore, the properties of LLP pollutants influence how leachate interacts with groundwater flow [12], which can be revealed by the anomalies in electrical resistivity profiles [38].

The physical and chemical properties of contaminants present in leachate, such as their solubility, mobility, and persistence, can influence the movement of leachate plumes [36,45]. Factors such as the solubility, density, and reactivity of contaminants can influence their transport through the subsurface. For example, highly soluble contaminants may travel more readily with groundwater flow, while denser contaminants may sink and spread laterally. Additionally, reactive contaminants can undergo chemical transformations that alter their mobility and behaviour within the plume [6]. Therefore, highly soluble and mobile contaminants are more likely to travel greater distances in groundwater. Understanding these properties is crucial for predicting and managing the movement of LLPs to mitigate potential environmental impacts.

3.4. Contents of Dissolve Substance

The content of dissolved substances in leachate plumes can vary depending on the composition of the waste materials in the landfill and the degradation processes occurring within the site. Leachate plumes can contain a wide range of dissolved substances, including but not limited to organic compounds [4,46]. Heavy metals (HMs), nutrients, inorganic salt and ions, dissolved gas, organic acid, pathogens and other dissolved substances. Organic compounds such as volatile organic compounds (VOCs) like benzene, ethylbenzene, xylene (BTEX), toluene, polycyclic aromatic hydrocarbons (PAHs), chlorinated solvents, and various other organic chemicals derived from the decomposition of organic matter and industrial waste are usually found in the LLP [47,48]. HMs such as lead, cadmium, zinc, chromium, mercury, and arsenic can be present in leachate plumes, which usually originate from the dissolution of metal-containing waste materials and industrial byproducts hipped at dumping sites [49,50]. LLPs may contain dissolved nutrients such as ammonia, nitrate, and phosphorus, which are derived from the decomposition of organic matter and the breakdown of phosphorus and nitrogen-containing compounds in the waste [18]. LLPs may also contain dissolved inorganic salts and ions such as carbonates, sulfates, chlorides, and other mineral constituents derived from the dissolution of waste materials and the leaching of soil and rock formations, while organic acids produced during the decomposition of organic matter in the landfill can also contribute to the acidity of leachate plumes, potentially leading to the presence of dissolved organic acids such as formic acid, acetic acid, and others [51,52]. Other Dissolved materials can also contain a variety of dissolved substances such as pharmaceuticals, dyes, surfactants, and other chemicals present in the waste materials may influence the mobility rate of LLP and impact the environment [53]. In summary, the specific composition of dissolved substances in LLPs may vary based on several factors such as the type and age of landfill wastes, the presence of hazardous or industrial waste, and the environmental conditions influencing LLPs generation and migration. Therefore, understanding the content of dissolved substances in LLPs is essential for evaluating environmental impact, and designing appropriate monitoring and remediation strategies, while protecting soil, surface water sources, and groundwater systems to safeguard its integrity.

3.5. Flooding

Flooding can have a significant influence on dumpsite leachate plumes when water infiltrates the waste materials and mobilizes the leachate plumes, causing it to spread and potentially contaminate surrounding soil and water sources. This increased water flow (flood) can transport leachate plumes over larger distances, impacting a wider area, which compromises the integrity of containment systems, such as liners and leachate collection systems [6]. In addition, floodwaters can erode dumpsite structures, leading to the potential release of solid waste and further contamination of the surrounding area [54]. Furthermore, flooding can affect the natural hydrology of the area, potentially altering the flow paths of leachate plumes and increasing the risk of contamination of surface water bodies and groundwater.

LLPs from poorly managed landfills can create groundwater-contaminant plumes, which can last for decades. Therefore, understanding the dynamics of leachate movement in space and time is quite essential for management, planning, monitoring, and assessing the risk to the surface and groundwater systems [1]. During the event of rainfall, the rainwater penetrating the dumpsite wastes forms leachate, which contains dissolved constituents and can potentially contaminate the surrounding environment [11]. This mobilization of leachate by flood to the near environment, especially from the unlined landfills. In the case of the Norman Landfill, a study shows that for more than a period of 23 years, the spatial extent of the leachate plume increased significantly. The leachate plume extended by 878%, from an area of 20,800 m² in 1986 to 203,400 m² in 2010 [55]. In calculating the linear plume velocity of leachate plumes, it was found that about 40.2 m/year, which compared favorably to the groundwater-seepage velocity of 55.2 m/year, while the plume-scale hydraulic conductivity values found within the alluvium soil varied between 7.0×10^{-5} to 7.5×10^{-4} m/s, with a median of 2.0×10^{-4} m/s. The concentration of Cl^- increased within the landfill subsurface, while downgradient from the landfill, the concentrations of Cl^- decreased during dry periods.

However, the landfill absorbed and retained the leachate plumes during wet periods, resulting in lower concentrated leachate downgradient [55]. On the contrary, the opposite occurred in groundwater downgradient from the landfill, where wet periods defused the leachate plumes within the landfill but increased leachate migration to produce a more concentrated contaminant plume [37]. In summary, understanding the LLP's behaviour is quite essential for monitoring, managing, and mitigating contamination risks associated with LLPs. Assessing and monitoring the expansion, migration, and concentration of LLP during variable hydrologic conditions provide invaluable insights for evaluating potential risks to downstream receptors [6]. In conclusion, flooding can exacerbate the influence of LLPs by increasing the potential for contamination and spreading the impact over a larger area. Therefore, proper management and mitigation measures, which include flood-resistant infrastructure and effective leachate management systems, are quite essential for minimizing the influence of flooding on LLPs.

3.6. Geological Composition

The geological composition of the subsurface can have a significant impact on the behaviour and impact of leachate plumes. The properties of geological materials such as nature, rock formations, and soil types control the movement and potential risks associated with leachate plumes. The impact of geological composition varies depending on the following factors:

a. The permeability and porosity of geological materials play a vital role in controlling the movement of LLP contaminants within the subsurface. Studies show that highly porous formations and permeable materials such as sand and gravel aquifers can trigger rapid migration of LLP pollutants, potentially leading to widespread implications on the integrity of groundwater systems [44,56]. However, very low-permeability materials such as clay layers can act as protective barriers, slowing the movement of LLP pollutants and providing natural attenuation to the environmental threat LLP [6,57]. These geological properties can also exhibit sorption and retention contaminants from LLPs. Sorption processes involve adsorption and ion exchange, which can affect the bioavailability and mobility of LLP contaminants, controlling the potential to migrate and impact surface water resources and regional groundwater.
b. The nature of area aquifers within certain geological compositions can significantly control the potential of LLPs to impact groundwater resources. The leachate plume pollutants may migrate more rapidly over greater distances within productive aquifers, threatening the integrity of the quality of drinking water [38]. The hydraulic properties of the subsurface play an important role in groundwater protection against subsurface contaminations

[58]. Study shows that a sufficient thickness of the subsurface layer combined with poor hydraulic conductivity can effectively protect groundwater reservoirs against soil layer erosion. This is because layered resistivity data were used to estimate the hydraulic conductivity of both aquifer sections and the overburdened thickness covering the aquifer. The estimated hydraulic conductivity of the aquifer zone is significantly varied between 0.337 and 10.62 m/day. On the other hand, the aquifer's overburdened soil strata showed low hydraulic conductivity values, ranging from 0.0721 to 0.639 m/day. This high hydraulic conductivity index can influence the groundwater mobility and the movement of LLP contaminants. Nonetheless, the overburden layers covering the aquifer units with low hydraulic conductivity nature suggested a strong aquifer protective capacity index against subsurface contaminations. This implies that LLP pollutants' movement depends on the hydraulic conductivity (permeability) of the subsurface materials. A high-conductivity material allows faster movement. Additionally, a porous media (such as sand) facilitates LLP pollutants flow, while clay-rich soils may hinder it. The spatial distribution of contamination plumes reflects these variations [38]. Therefore, understanding the hydraulic properties of aquifers is essential for assessing the vulnerability of groundwater to leachate contamination.

c. Groundwater flow pathways: The routes and rates of groundwater flow are shaped by the geological composition, which also affects the migration and dispersal of leachate pollutants [57]. The spatial extent and possible dangers associated with leachate plumes can be affected by variations in geological materials that result in preferential flow pathways, fractures, and conduits that either facilitate or hinder the transport of contaminants [1]. The interactions between surface water bodies and groundwater are typically influenced by the groundwater-surface interactions, which may have an impact on the movement and fate of LLP pollutants in aquatic environments [59]. The velocity, direction, and recharge rates of groundwater systems play a significant role in the LLP expansion and attenuation [1,38]. Therefore, evaluating the possible threats to surface water quality and ecological receptors requires an understanding of these interconnections. The behaviour and influence of leachate plumes are typically significantly impacted by the subsurface's geological composition. This includes elements including migration trends, environmental risks, and the effectiveness of management and cleanup efforts. To assess and mitigate the ecological effects of leachate plumes and protect the quality of surface and groundwater, it is imperative to comprehend these geological components. In summary, understanding the interplay between contaminant properties, hydrogeology, and seasonal variations is crucial for assessing the risk posed by leachate plumes from dumpsites. Monitoring and modeling these factors help inform management strategies and protect groundwater and surface-water resources

3.7. Hydrogeological Conditions and Groundwater Flow Dynamics

The movement of leachate plumes is influenced by the hydrogeological characteristics of the surrounding environment, such as the permeability of the soil and the presence of geological features like fractures and faults. These factors can affect the flow of groundwater and the spread of contaminants. Leachate plume migration is largely determined by the natural flow of groundwater [57], which is governed by geography, aquifer features, and hydraulic gradients. Predicting the possible movement of contaminants requires an understanding of the dynamics of groundwater flow in the area [10]. The migration, dilution, and transport of contaminants from leachate plumes can be greatly influenced by groundwater flow, which ultimately shapes the pollutants' environmental impact. Leachate plume effects can be influenced by groundwater flow dynamics, as demonstrated by many important elements. The routes and rates at which leachate pollutants travel through the subsurface are determined by the direction and velocity of groundwater flow [1]. Leachate plumes can be transported by groundwater flow in a variety of paths and distances, which may have an impact on the degree of contamination and the places that are at risk. The dispersion, dilution, and potential interaction of contaminants with geological formations and aquifers are all influenced by the flow dynamics of groundwater [1], which governs their movement within leachate plumes. The direction and speed of groundwater flow can influence downstream effects on ecosystems and water resources by influencing the rate of contamination spread.

The subsurface's hydrogeological characteristics, such as soil types, permeability, porosity, and hydraulic conductivity, combine with the dynamics of groundwater flow to affect the transport and retention of pollutants from leachate plumes [59]. Changes in these characteristics may have an impact on the possibility of attenuation or retention in the subsurface as well as the rate of pollutant migration. Over time, a landfill leachate plume's spatial spread may expand. For instance, a study shows that for 23.4 years, the leachate plume from the Norman Landfill greatly increased [1]. Determining the behaviour of plumes aids in evaluating the threats to surface and groundwater resources. In general, leachate plume behaviour and effects are greatly influenced by the dynamics of groundwater flow, which also shapes environmental risks, migration patterns, and the efficiency of management. Based on the influence of hydrogeological conditions and groundwater flow dynamics, it is advisable landfill be located at a site where the aquifer system is deeper to mitigate surface contaminants like LLPs. Where this is difficult to achieve, the landfill should be located at least 5.0 m above the area aquifer system. Figure 2 demonstrates the groundwater pollution emerging from a waste disposal site alongside the topography of underground water, which has a significant influence on the LLP contaminants in the groundwater systems based on the various depths illustrated. Comprehending these dynamics is crucial for evaluating and alleviating the ecological consequences of leachate plumes and safeguarding the quality of surface and groundwater.

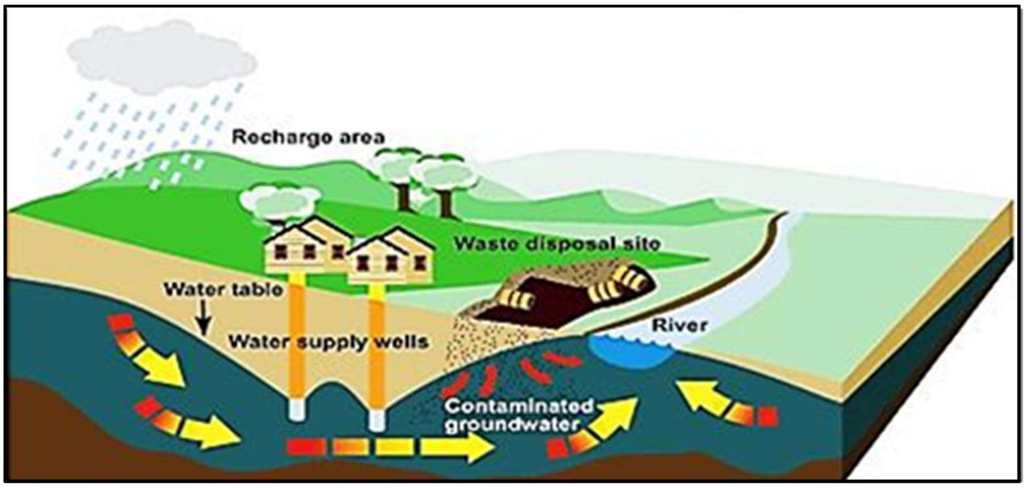

Figure 2. Groundwater Contamination from a waste disposal site [60].

3.8. Human Activities

The challenge of waste management is a global concern, which may not be resolved soonest, as long as human activities continue [61]. Human activities such as environmental indiscipline, industrialization, population expansion, waste burning, dumping of waste in waterbodies, and agrochemical practice have a significant impact on the degree of generation and spread of leachate plumes from landfills [6]. A recent study showed that illegal dumping (improper disposal of waste) in unauthorized areas can lead to the formation of unregulated and poor landfills without adequate containment measures [62]. A remarkable study conducted in Nigeria shows that a good percentage of waste generation in the country is being dumped illegally such as waste dumping in waterbodies, gutters, and burning, with adverse effects on the environmental matrices and public health [6]. The dumping of solid waste in open spaces, drainage systems, and water bodies significantly contributes to the generation of leachate plumes as rainwater infiltrates through the waste and picks up contaminants. Inadequate waste segregation and recycling practices remain one of the influencing factors affecting the production of LLP contamination and potentially posing risks to human health and ecosystems [1,63]. Urbanization and land use changes such as rapid urbanization and industrialization can increase waste generation thereby exacting pressure on the available landfills. This can increase the risk of contamination from leachate plumes spreading to populated areas, exposing communities to health hazards.

Another human activities that has influenced the impact of LLPs is waste burning, which is readily common in developing countries. The burning of mix-waste streams accumulated at dumpsites can produce uncontrolled and spontaneous fire incidents offering major environmental dangers [10,64]. As a result, the people who live close to these dumpsites are susceptible to environmental risks like smoke and disagreeable odours. The repercussions of burning waste still pose a threat to environmental sustainability and security, despite the practice's apparent ease of use and simplicity. It is unpredictable how much burning waste may harm the environment and public health. Waste fires remain a powerful catalyst for the environmental disaster, which is getting worse and needs to be addressed immediately [61]. Developing and lowincome countries are disproportionately affected by this dilemma since there is a widespread prevalence of uncontrolled disposal and open-air burning. This is because the open garbage fires are breeding grounds for a variety of environmental dangers, such as soil erosion and pollution of the air and water. It is also observed that waste burning is one of the major sources of greenhouse gas emissions that exacerbate global climate change and add to the growing issue of marine litter [61]. Unfortunately, waste burning is still being practised in most developing nations due to the high costs associated with contemporary waste management technologies (WMTs), which place a substantial burden on the governments because the WMTs have not yet gained the widespread adoption seen in other nations [14]. In addition to this, waste fires provide short- and long-term health risks to humans (skin and respiratory ailments as well as more serious health consequences including cancer) based on their negative effects on the environment. Addressing human activities and Environmental indiscipline that exacerbate the generation and mobility of LLP pollutants requires a combination of regulatory enforcement, public awareness, and sustainable waste management practices. This will promote responsible waste disposal, recycling, and pollution prevention, the risks associated with leachate plumes can be minimised to protect human health and the environment.

3.9. Landfill Design and the Site Conditions

Poor landfill design and site conditions have a significant influence on the generation and mobility of LLP pollutants, leading to increased environmental and health risks. A poorly designed landfill lacks adequate liner systems such as clay or synthetic liners to prevent leachate infiltration into the surrounding soil and groundwater systems. Without effective liners, LLP pollutants freely percolate through the waste layers contaminating the soil systems down the the table water. Inadequate LPP collection systems are another limitation of poorly designed landfill collection systems that will encounter pitfalls in collecting and managing LLP efficiently. This increases the risk of LLP formation and mobility. In addition, insufficient leachate collection and management systems to capture and treat the LLP effectively can result in the leachate plume buildup within the landfill, potentially increasing the risk of leaks and seepage into the environment [56,65]. A remarkable study in Nigeria shows that a poorly designed landfill can slope instability or landslide [6]. According to a recent study, the leachate plumes penetrating the soil could metamorphose into influencing factors annihilating the load-bearing capacity of the uppermost topsoil, potentially causing landslide and structural failures [6]. In addition, unstable slopes in poorly engineered landfills can also lead to rapid mobility of LLP downhill, potentially washing down into groundwater aquifers [41]. Slope failures can also breach the liner systems of a landfill, allowing leachate plume to escape. Slope instability or failure can lead to erosion, potentially risking the LLPs spreading beyond the landfill boundaries. In addition, the degradation of organic materials and the presence of toxic substances have a significant impact on the quality of soil surrounding landfill sites, which in turn has a compounding effect on biodiversity effects on the surrounding vegetation. Landfill areas have an impact on the natural surroundings and landscape; they smell, develop a trashy visual appearance, and become a source of bacteria; the presence of vermin, polluted traffic, and noisy conditions accompany landfills, which lowers land prices; the vermin are the main cause of diseases, the main cause of many adverse birth defects, health issues, respiratory illnesses, and cancer—all of which are linked to landfill site exposure [66].

The resultant effects of these LLPs seeping the ground soil can persist for longer periods, compromising the integrity of the groundwater quality [9]. Therefore, adequate monitoring and maintenance of landfills are very important to identify potential issues earlier and prevent the formation of leachate plume accumulation, which a poorly managed landfill is more likely to experience breaches, leaks, and other failures that can lead to the flowing of leachate plumes into the environment. Effective planning, construction (Figure 3), operation, and maintenance of landfills are essential in managing the potential impact of LLP on surrounding ecosystems and communities [67]. In conclusion, poor landfill design and site conditions can exacerbate the generation and mobility of LLPs, which inversely increase the risk of environmental contamination and health hazards. Addressing landfill design flaws, implementing effective liner systems, and optimizing waste management practices are essential to minimizing leachate plumes and safeguarding groundwater resources.

Therefore, the design and operation of landfills significantly have impacted the movement of leachate plumes. In designing engineering landfill, factors such as the management of leachate collection systems [12,68], and the presence of barriers can influence the direction and extent of leachate migration [69,70], rainproof to prevent rainwater percolator the waste materials and the placement of liners [6]. Minimize the impact of rainwater on landfills involves several strategies, which include but are not limited to covering landfills to prevent rainwater from infiltrating the waste (Figure 3), adequate landfill design such as good drainage systems to collect direct rainwater away from the waste and into treatment facilities, leachate plume collection within the landfill and transport it to treatment plants, and surface vegetative cover, which helps absorb rainwater, stabilize soil, and reduce erosion.

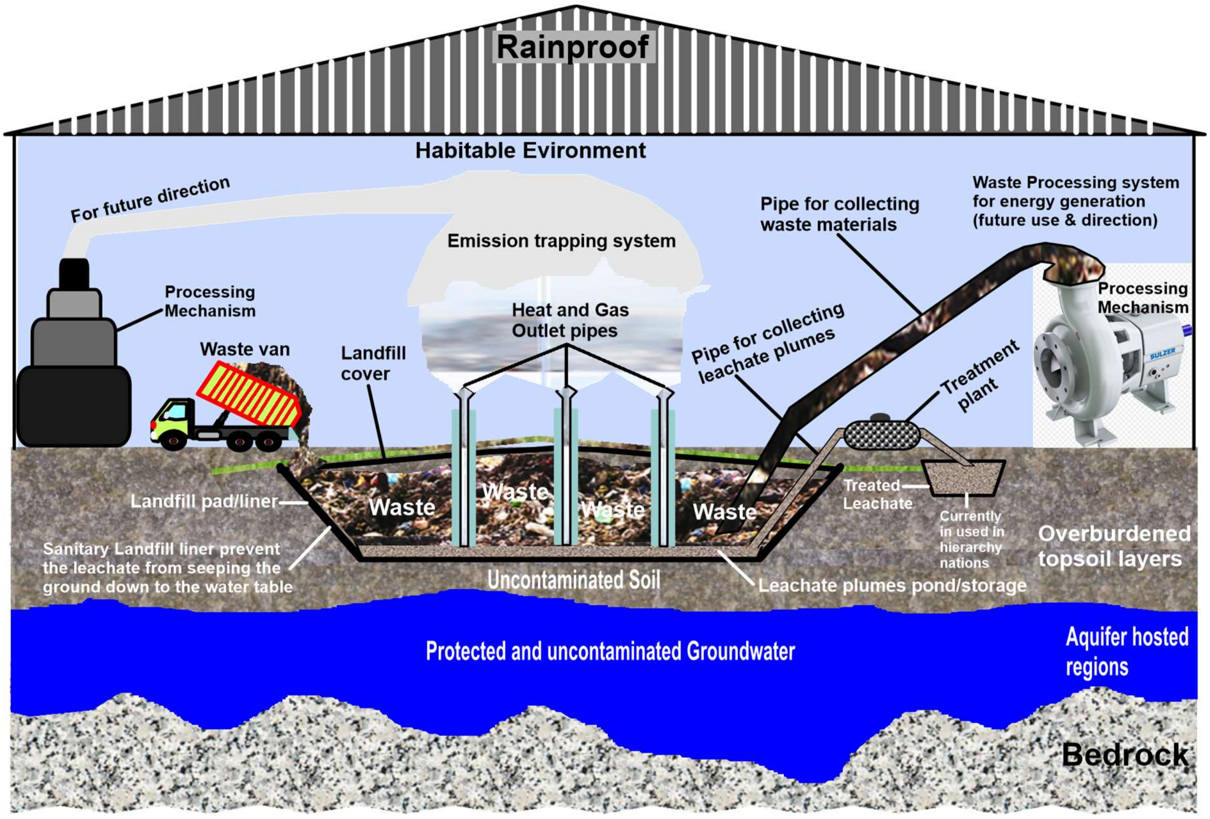

Figure 3. A proposed modern sanitary landfill for future direction [6].

4. Health Implication

The LLPs have several health implications due to the potential contamination of soil, surface water sources, and groundwater. The common associated health risks with LLPs include (i) contamination of drinking water, (ii) spread of diseases, (iii) airborne contaminants, and (iv) degrading ecosystems. The LLPs pollutants can contaminate groundwater sources, which may be readily used for drinking water supply, exposing the contaminated drinking water to various health issues, including skin irritation, gastrointestinal problems, fatigue, joint pains, and potential long-term health effects from exposure to harmful chemicals [41,65,71–73]. The LLPs contain some pathogens and bacteria that can spread to environmental vital organs [29,74,75] such as soil, surface water sources, and groundwater, which potentially increase the risk of waterborne diseases such as typhoid, cholera, and other infections. The LLPs can also release volatile organic compounds (VOCs) and other harmful gases into the atmosphere to pollute air conditions [75], especially in areas with poor ventilation. Inhaling this pollutant can lead to respiratory problems, headaches, and other health issues. The LLP contamination is highly injurious to the local ecosystems, including aquatic life in rivers and streams, biodiversity, and vegetation, which can cause an imbalance in the ecosystem and impact the health of animals, fish, plants, and humans that rely on these resources [10]. Because of the range of toxins that LLPs release into the environment, they may have a substantial impact on one's health. For example, leachate frequently contains heavy metals like lead, mercury, and cadmium, which can result in major health consequences like kidney failure, neurological damage, and developmental disorders in children [74]. Infectious diseases, especially those of the gastrointestinal tract, can be caused by bacteria, viruses, and other pathogens that LLPs may carry [74]. For example, elevated ammonia levels can result in nitrate production, which can eutrophicate water bodies and create "dead zones" where aquatic life cannot exist. Elevated nitrate levels in humans can result in methemoglobinemia, sometimes known as "blue baby syndrome" in newborns [75]. Certain newly discovered pollutants in leachate can disrupt hormone systems, which may result in concerns with reproduction, development, and other health consequences [43]. For this reason, it is essential to manage landfill leachate properly to safeguard the environment and public health. In addition, due to organic waste degradation, over 65% of landfill wastes comprise organic biodegradable matter from homes, businesses, and industries. These materials emit an unpleasant stench. The breakdown products release methane, a potent greenhouse gas that absorbs more than 65% of the extra heat that CO_2 produces in the atmosphere. Methane from landfills can contribute to the production of electricity and produce CO_2, a byproduct that lessens the effects of global warming [76]. The routine health monitoring of residential society and those living close to waste facilities and landfills is not supported or maintained by the health information and management system. Therefore, every nation must have the tools and expertise required to carry out environmental and health risk assessments. This component should be taken on a priority basis, and critical progress to build and protect public health linked with possible environmental risks. To construct and justify the basic issues of this, there are plans and recommendations for a National Landfill-associated Environmental and Human Health Action Plan [77]. To mitigate against these risks, sustainable waste management practices and advanced and combined approaches such as geophysical approach, physiochemical investment, recycling, proper landfill design, and effective leachate treatment are essential. Therefore, authorities such as environmental stakeholders and decision-makers need to manage and monitor landfill sites properly to prevent the further spread of LLPs and minimize the associated health risks.

5. Way Forward

Most of these influencing factors are naturally occurring factors, which may be difficult to remedy. However, understanding these factors would enable the environmental stakeholders and decision-makers to control its impact earlier by avoiding certain geological locations, while embracing safe depth and distance as the way forward. The safe depth and distance become essential since the concentrations of LLP contaminant decrease as the distance from the source increases [12]. The compiled literature shows that the LLPs remain a major threat to the environmental vital organs such as air conditions, soil, surface water sources, and groundwater. Additionally, a continuous trend of decreasing physicochemical parameter concentrations was seen as the surveys moved farther away from the dump. The significance of treating leachate through a modern engineering landfill (Figure 4) for discharging solid materials is highlighted by this research as the way forward.

Furthermore, an appropriate landfill liner is essential to stop leachate from entering water sources, which affects summer, fall, and winter engineering. In terms of pH, electrical conductivity (EC), total nitrogen, phosphorus, potassium, calcium, magnesium, zinc, iron, copper, manganese, temperature, turbidity, and biological and chemical oxygen demand (BOD and COD), the leachate outflow site showed the highest mean values. The safe distance and depth from leachate plumes are critical factors that can significantly influence the potential impact of leachate migration on the surrounding environment. Safe distance and depth as used by Alao, et al., [6] implies a distance and depth far away from the pollutant source (landfills) at which a well or other water source can be sited with little or no impact. These parameters play a crucial role in determining the extent of contamination, the vulnerability of receptors, and the effectiveness of containment and remediation measures. In addition, the safe distance from a leachate plume refers to the spatial separation between the source of contamination (e.g., the landfill) and sensitive receptors such as drinking water wells, surface water bodies, and ecological habitats. Establishing a safe distance is quite essential for minimizing the potential risks of groundwater and surface water contamination from LLPs. According to Alao, et al., [10], a greater safe distance can reduce the likelihood of contaminant migration to receptors, providing a buffer zone for protection.

Safe distance is not limited to the distance of wells or water sources far away from LLPs but also can be applied to the distance at which landfills should site away from residential areas. This can directly influence the vulnerability of receptors to contamination, which a greater distances can reduce the risk of exposure and potential impacts on human health, aquatic ecosystems, and agricultural resources. Safe distances are typically determined based on geophysical and geochemical investigation. Previous studies show that the depth of leachate plumes within the landfills and the ambient extend to 15 m maximally. Therefore a deeper water source may pose less threat to the public and aquifer integrity. That is, the deeper leachate plumes can interact with groundwater flow dynamics, influencing the pathways and rates of contaminant migration. However, the deeper plumes may exhibit different transport behaviours and residence times within the subsurface, affecting the potential for off-site impacts and the design of containment and remediation strategies. In conclusion, safe distance and depth are quite important considerations for monitoring and assessing the environmental impact of leachate plumes, providing a framework for protective measures, regulatory compliance, and the sustainable management of landfills to safeguard the environment and public health.

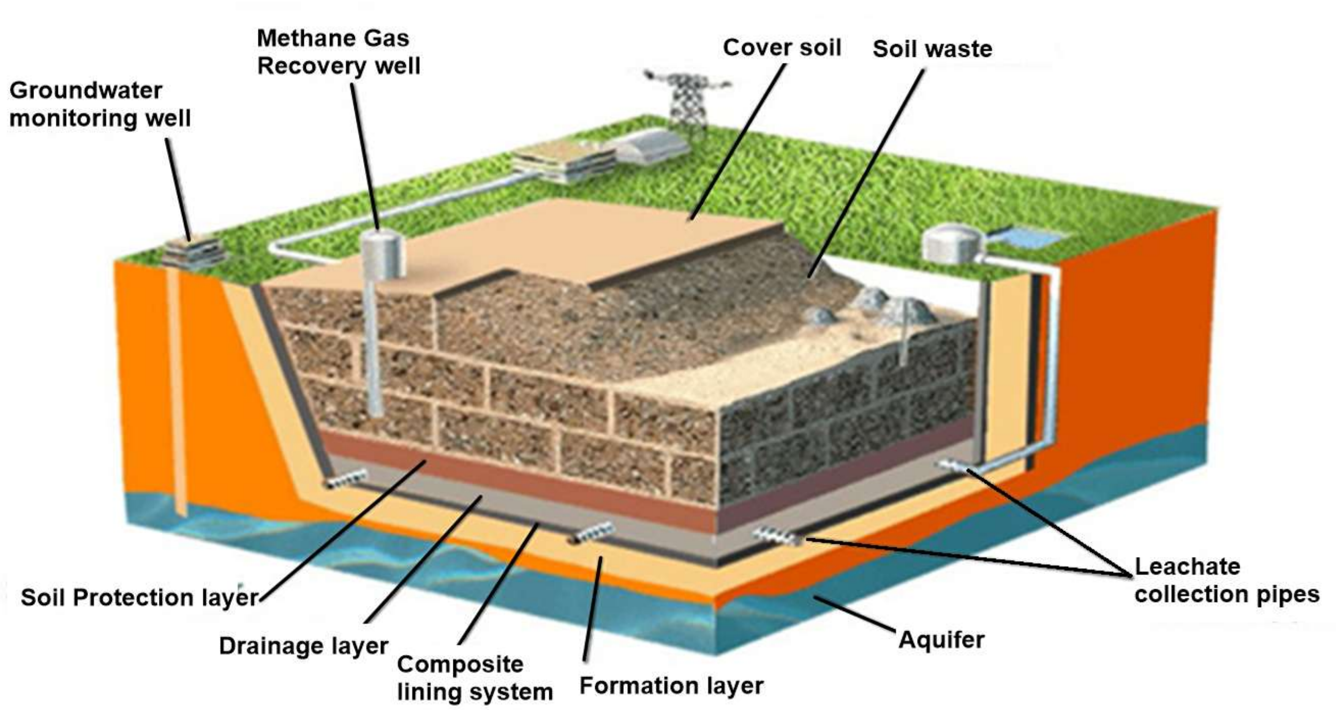

Figure 4. Typical Sanitary Waste Solid Landfill Design for Safeguard Environment [68].

6. Conclusion and Recommendations

The emergence of LLPs remains a significant environmental concern due to the potential threats to soils, surface water, groundwater., and public health. This study explores the factors influencing the spread of contaminants from LLPs into the surrounding environment, focusing on geophysical and geochemical perspectives. Geophysical methods play a crucial role in identifying the extent and movement of LLPs in soils, surface water, and groundwater. Techniques such as electrical resistivity imaging, ground-penetrating radar, and seismic surveys can provide valuable information on the subsurface characteristics and pathways of contaminant migration. Understanding the geophysical properties of the subsurface can help in delineating the spatial distribution of contaminants and assessing the potential risks to the surrounding environment. The geochemical processes also play a significant role in influencing the behaviour of contaminants in LLPs. Factors such as pH, redox conditions, mineralogy, and organic matter content can impact the mobility and fate of contaminants in soils, surface water, and groundwater. Geochemical modeling can help in predicting the interactions between contaminants and the surrounding environment, providing insights into the long-term behaviour of LLPs. The interaction between geophysical and geochemical factors is essential in understanding the complex dynamics of LLP contaminants in soils, surface water, and groundwater. Integrating geophysical and geochemical data can help in developing effective strategies for monitoring and remediation of contaminated sites. Furthermore, the identification of key factors influencing contaminant transport can aid in the development of sustainable management practices to mitigate the environmental impacts of LLPs. In conclusion, a multidisciplinary approach combining geophysical and geochemical perspectives is essential for understanding the factors influencing the spread of LLP contaminants in soils, surface water, and groundwater. This study highlights the importance of influencing factors of LLPs based on geophysical and geochemical data to address the challenges associated with LLP contamination and to protect the environment and human health.

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