Engineering and Technology Journal 42 (11) (2024) 1327-1342

Engineering and Technology Journal
Journal homepage: https://etj.uotechnology.edu.iq

Clay barriers performance in landfills: A review

Check for updates

Kawther Y. Al-Soudany*, Mohammed Y. Fattah, Falah H. Rahil

Civil Engineering Dept., University of Technology-Iraq, Alsina'a street, 10066 Baghdad, Iraq.
*Corresponding author Email: kawther.y.alsoudany@uotechnology.edu.iq

HIGHLIGHTS

- Installing a liner system keeps wastes separate from the environment and attenuates leachate contaminants
- Weather, compaction degree, and solid waste composition influence leachate production
- Bottom liner permeability is crucial in determining contamination transport through liner systems
- Clays are locally accessible and cost-effective for landfill containment at or near dumping sites

ARTICLE INFO

Handling editor: Mahmoud S. Al-Khafaji

Keywords:
Barrier performance
landfill liner
Review
leachate pollutants
Compacted clays

ABSTRACT

Clay barriers have garnered much interest in environmental engineering because they successfully reduce various ecological dangers, including groundwater contamination, the migration of leachate from landfills, and waste disposal in landfills. This review paper aims to provide a comprehensive analysis of the features, uses, and performance of clay barriers in various environmental conditions. The problem this review paper addresses is the dangers of waste disposal sites, which emphasizes landfills' harm to the ecosystem and explains why natural clays are often employed as barriers surrounding landfills to keep out pollution. The paper aims to provide an update on essential subjects about barrier system performance difficulties for landfills and their function in reducing the effects of pollutants on the surrounding environment. When designing physical barriers, it is essential to account for a certain amount of material degradation and ensure that the barriers will work for the time needed to achieve landfill sustainability.Subsequently, the elements that affect clay barrier performance are discussed in the study. These variables include long-term stability, chemical compatibility, hydraulic conductivity, and compaction techniques. The usefulness of clay barriers in practical applications is shown via case studies and experimental results. This illustrates the role of clay barriers in preventing the spread of pollutants and safeguarding natural resources.The paper also covers current advancements and new directions in clay barrier technology. These advancements include the use of nanomaterials, barriers made of geopolymers, and innovative construction techniques. The paper also addresses challenges related to the effects of aging, maintenance needs, and regulatory issues. It also provides viable ways to address these obstacles.

1. Introduction

Over the last two decades, the population has proliferated, which has resulted in a significant rise in the generation of municipal solid waste (MSW). The pertinent query is handling these solid wastes [1,2]. Recycling, composting, anaerobic digestion, incineration, disposal in the sea, and landfilling are general management techniques for MSWs [3,4]. Sanitary landfilling is the most popular way to eliminate MSWs since it is affordable, particularly in poor and undeveloped nations [5]. For instance, around 100% and 73% of collected MSWs in South Africa and China were landfilled [6,7]. Despite being extensively used, waste management nevertheless poses a growing environmental danger. Due to leachate leakage from landfill sites, the landfill often causes groundwater pollution [8-10]. The environmental effect of the facility is closely tied to its design and long-term performance since the bottom barrier (see Figure 1) is meant to reduce the migration of pollutants from the facility [11,12]. According to the European waste disposal law [13], landfills must be placed and constructed in such a way as to avoid soil, groundwater, or surface water contamination and to enable effective leachate collection.

Therefore, the capacity of liners to prevent seepage and bind contaminants is essential for landfill design. The permeability of the bottom liner is a critical factor in the movement of pollutants via liner systems, as noted by [14-16]. In contemporary landfills, a Geomembrane (GMB) and a Compacted Clay Liner (CCL) or a GMB, a Geosynthetic Clay Liner (GCL), and a Soil Liner (SL) are often used as composite liners [17-21]. Natural clay soil has a high sorption capacity, excellent structural stability

http://doi.org/10.30684/etj.2024.148162.1724
Received 24 March 2024; Received in revised form 14 June 2024; Accepted 18 June 2024; Available online 02 August 2024
2412-0758/University of Technology-Iraq, Baghdad, Iraq

over the long term, and limited permeability, according to [22], is a desirable liner material. However, a significant quantity of clay minerals must be used during construction to achieve a landfill liner's anti-seepage criteria and pollutant-blocking capabilities [23].

According to [24,25], two kinds of liners are now employed in contemporary landfills: synthetic liners, which are generally made of High-Density Polyethylene HDPE, and natural liners, which are typically composed of compacted clay. Although they require a high level of technological investment and are susceptible to slope stability, interface shear strength, and physicochemical, thermal, and mechanical issues [26], synthetic liners offer impermeability to leachate over the long term. Still, they may need to improve within 10 years of service [27,28]. The liners made of compacted clay are impermeable and have beneficial reactive qualities. Still, they may become unstable when in contact with leachate and are vulnerable to cracking when subjected to frequent wetting and drying cycles [29,30]. Liners used in landfills and other waste containment facilities are subject to certain requirements and limitations on the hydraulic conductivity value. A liner's hydraulic conductivity, denoted by the letter "k," is its capacity to allow fluids like water to pass through its porous structure. Waste liners with low hydraulic conductivity are ideal to prevent toxins from seeping into the environment. Regulatory authorities and technical standards usually set maximum acceptable hydraulic conductivity values for waste liners to guarantee efficient containment of hazardous pollutants. Disposal type, geological and hydrological characteristics of the site, and environmental rules are some variables that could cause these requirements to change.

The use of compacted clay barriers to stop the leakage of toxic substances from landfills has been successful. These liners may experience shrinkage, cracking, desiccation, and loss of integrity if the material used for them does not meet the standards set by the CPCB-2001 and the USEPA in 1989, which state that permeability should be at least 10−9 m/s and unconfined compressive strength should be at least 200 kPa. Landfills are potential "ticking time bombs" because containment liners ultimately fail independently of their low permeability characteristics. If rainfall is allowed to enter the waste, waste degradation is increased, which speeds up the stabilization of the waste, increasing this reactivity (or attenuation) [31]. Natural liners' attenuation capabilities lead to shorter periods of (1) possible pollution discharge and (2) aftercare monitoring, resulting in cheaper landfill costs and less environmental contamination risk. But historically, the impermeability of liners has received the majority of attention as a performance attribute. Instead of depending exclusively on the impermeability (or containment) function, we concentrate on both impermeability and attenuation capabilities as a foundation for enhancing liner design and performance. The technical design of compacted clay liners may include this dual potential to handle both organic and inorganic contaminants in leachate [32,33]. In landfill liner systems, compacted clay liners are more appealing than synthetic geomembranes on their own due to their attenuation capacity, low cost, and simplicity of application. This is crucial for eliminating organic contaminants [34] and for low-income nations where more than 90% of garbage is publicly deposited [35].

However, the feasibility of the clayey substratum as a prospective liner has to be adequately assessed since clays have a wide range of physicochemical characteristics [36,37]. This problematic process must consider all the variables and how they interact with one another to prevent any negative consequences on the leachate-liner system. The liner construction is more challenging, and the possibility of swelling, shrinking, and cracking as a failure mechanism is more substantial if the clay plasticity is too high. One hundred and sixteen references were chosen for this study's inclusion; they fulfilled the primary requirement that the given data be accurate and originate from well-defined sources. The findings of this paper may significantly impact the management of landfills and waste disposal. A landfill's physical barriers (top and basal) are the contact between the landfill and the outside environment (subsoil and atmosphere). The function of barrier elements (drainage, liner, and reactive layer) in regulating the transfer of mass (leachate, gas, water, and pollutants) via interfaces is discussed in this paper. Materials and products are detailed with several potential combinations in light of the primary design requirements.

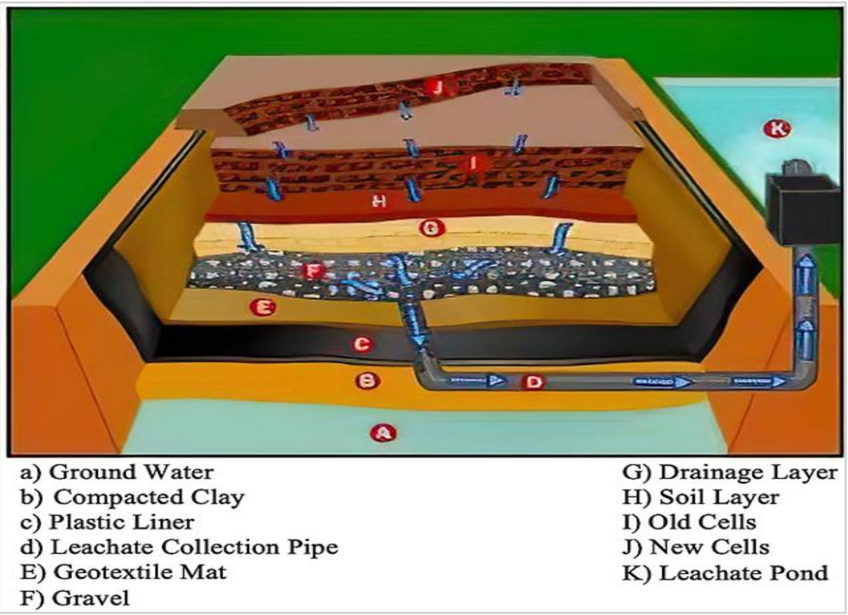

Figure 1: Diagram of a municipal solid waste landfill showing a cross section [38]

2. Containment of wastes

Landfills remain the primary disposal option for most waste in many other nations worldwide; even in regions with extensive waste pretreatment (such as northern Europe), landfills are still significant as the final disposal point. Biodegradable waste will break down via biological processes. The pace of deterioration may range from the quick breakdown of plant materials to the comparatively sluggish cellulose in paper and cardboard. Even though most polymers are prone to biological and chemical activity, only a few waste kinds (such as polyethylene, glass, and inert soil) may be considered "inert." Other waste materials will disintegrate like this. According to the Department of the Environment [39], this biodegradation of waste produces landfill gas, a mixture of methane (60%) and carbon dioxide (40%), as well as minute amounts of several longer-chain hydrocarbons that contribute to a characteristic aromatic odor. The decomposition process's by-products are leached due to water penetration via decaying wastes, creating a liquor known as "leachate." Strong 'acetogenic' leachate is produced in the early phases of decomposition [40,41].

Both of these leachates are powerful effluents, having, for instance, far greater pollutant concentrations than conventional sewage. The chemical and biological oxygen requirements may cause significant drops in the quantity of dissolved oxygen in any receiving waters, hurting aquatic life. Ammonia is a harmful chemical that may harm water as a resource in low quantities, according to the [42]. Even very modest levels of chloride may harm the quality of water sources. Without a doubt, it is essential to safeguard the ecosystem from the harmful effects that might arise from the migration of landfill gas or the leaking of leachate from wastes disposed of at landfill sites Figure 2 details of a sanitary landfill (a) The leachate collection system, the suitable lining system, and the gas collection system are all present in landfills. (b) Leachate treatment plants and exploitation of collected gas to generate electrical energy in landfills [43].

The following are often combined to obtain this Figure 3:

1) The process of removing landfill gas in a carefully controlled manner by active pumping from wells located inside the landfill, followed by flaring and utilization (such as the generation of electricity), hence reducing the likelihood of off-site migration.
2) Leachate will be collected and removed from the landfill by building a drainage system. This will prevent the leachate from escaping into the ecosystem around the landfill.
3) Installing a liner system to keep wastes isolated from the environment as much as possible.
4) Installing a capping layer decreases the precipitation that penetrates the landfill, which minimizes the quantity of leachate produced and prevents the uncontrolled release of landfill gas into the atmosphere [40]. Methane is a dangerous greenhouse gas, and releasing it without control is no longer acceptable.

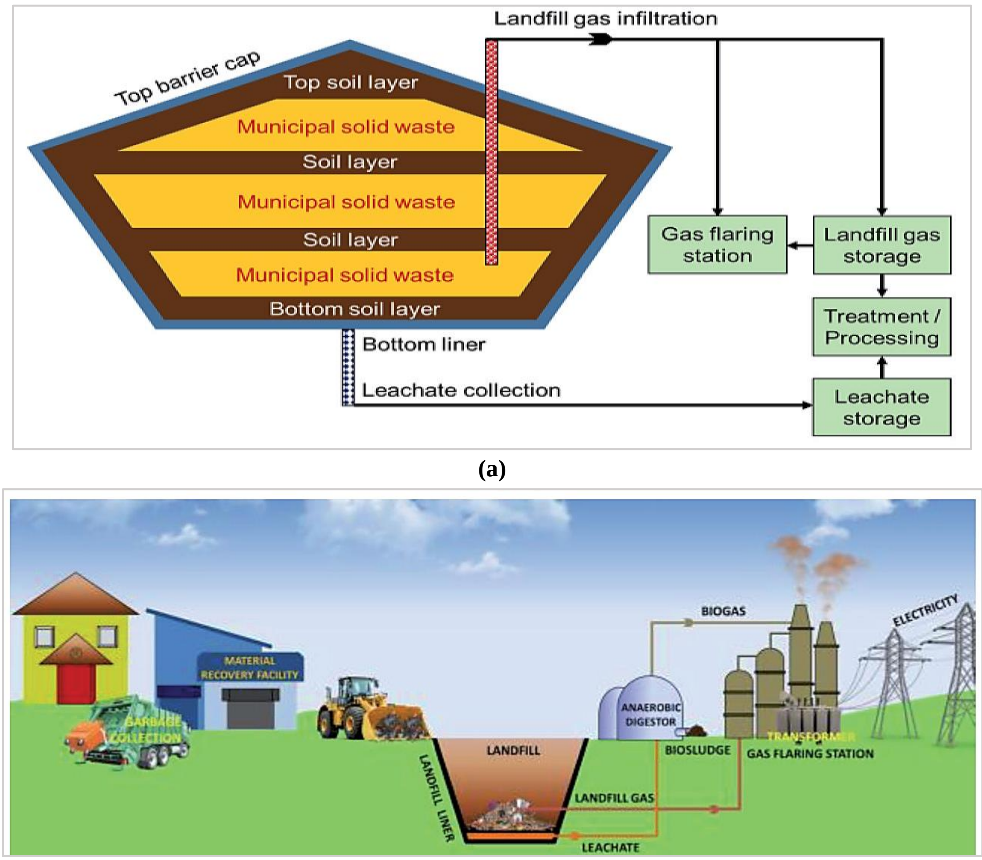

Figure 2: Details of a sanitary landfill (a) processes (b) structural [43]

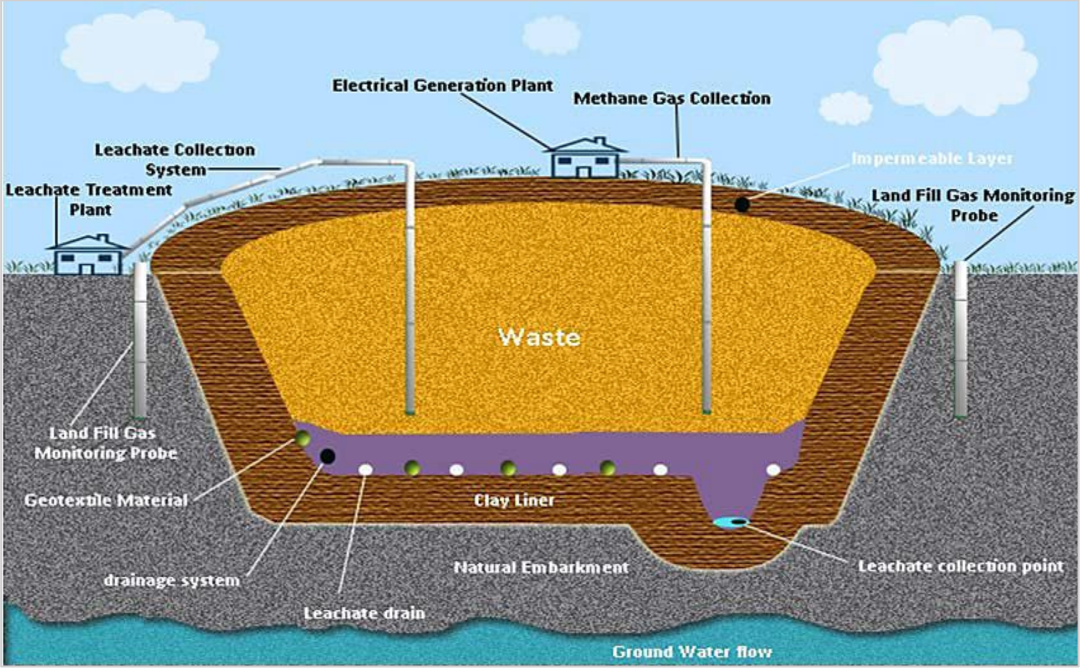

Figure 3: Schematic representation of a landfill's leachate and gas management systems [44]

3. Landfill liner

If leachate from a landfill escapes and contaminates the area, such as groundwater, serious environmental and health risks might exist. To lessen the effects of a landfill on the environment and public health, when it comes to the design and construction of landfills, the essential function is to contain toxic gases and liquids [45,46]. Another key landfill goal is appropriately collecting and transporting the leachate to a facility for further treatment. According to [47], landfills must serve as a hydraulic barrier to stop leaks or as an effective system for collecting and treating leachate. In MSW landfills, barrier functions may be achieved by alternating layers of low-permeability materials [48-51].

The liner reduces landfill pollution by effectively controlling and isolating the leachate generated within a landfill see Figure 4. To choose the best landfill liner, one must consider characteristics like absorptivity, shear strength, and other variables [52] [53]. As was already said, an engineered landfill primarily comprises a bottom liner to lessen groundwater contamination and leachate production. According to [54], liners are often composite sheets constructed of geomembrane placed on top of a clay liner. Compacted clay layers may absorb many leachates for a low cost, but strong bases and acids can dissolve solid materials within the clay, creating channels [55]. As a result, leachate fluids with pH values of 4 or above often need the most attention.

Several variables, such as the weather, the degree of compaction, and the makeup of solid waste, influence leachate production.

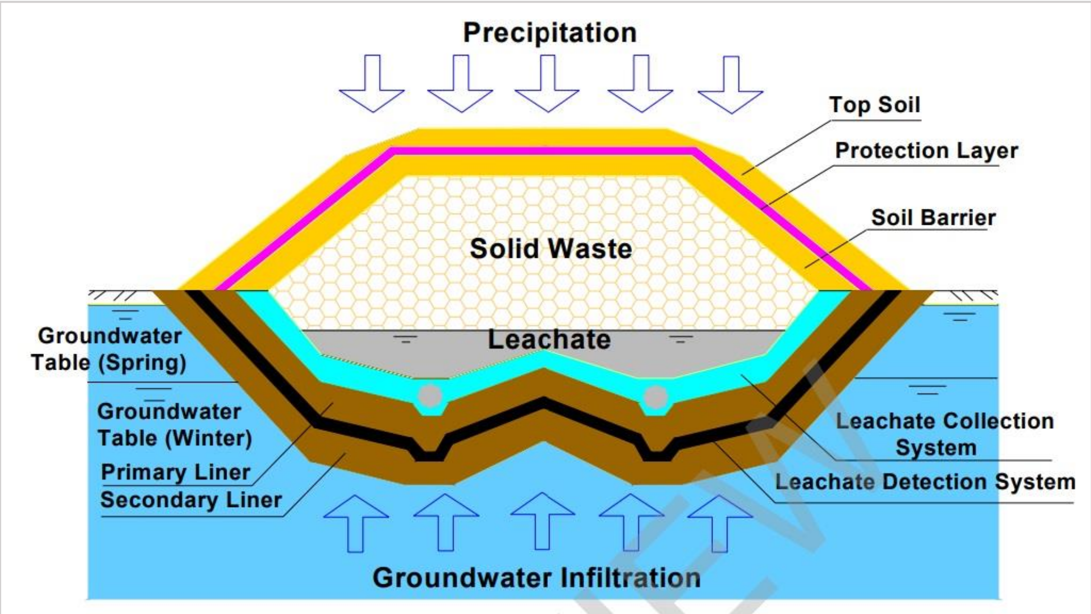

Figure 4: Cross section of an idealized landfill system [56]

4. The installation of clay barriers in landfills

Clay is used in landfills for a variety of reasons, the majority of which have more to do with design. The capacity of liners to absorb contaminants is vital for constructing landfills. According to [57], the permeability of the bottom liner is the most critical factor in determining the amount of contamination transported through liner systems. Natural clays quickly established themselves as suitable materials for use as environmental barriers surrounding landfills, either as an in-situ material or engineered liner or capping layer. This was accomplished by using natural clays either as an in-situ material or as an engineered liner. Composite liners are quite common in contemporary landfills. These liners often include either a Geomembrane (GMB) and a Compacted Clay Liner (CCL) or a GMB, a Geosynthetic Clay Liner (GCL), and a Soil Liner (SL) [58-60].

Composite liners are highly popular. According to [61], natural clay soil is an ideal liner material due to its high sorption capacity, long-term structural stability, and low permeability. Building a landfill liner to fulfill the anti-seepage criteria and pollutant-blocking capabilities always consumes a substantial quantity of clay minerals [62]. Although clay minerals are natural resources that do not regenerate, they are considered non-renewable. The following is a synopsis of the primary benefits that come from making use of clays.

1) Cost: Clays, where they are accessible locally, either on or adjacent to the dumping site, are the most cost-effective method for providing landfill containment.
2) An inability to absorb water: Because of the microscopic particle size of their constituent particles, clays have a very low permeability, which translates to meager seepage rates for the fluids in landfills.
3) Resistance to damage: Thick clay barriers are often more resistant to being damaged than their synthetic equivalents, which are thinner.
4) Accessibility: Due to the broad distribution of clays around the globe, it is guaranteed that materials with poor permeability will be found near most waste disposal locations.
5) The capacity to coexist with chemicals: Clay minerals are the end-product of geological weathering, which may take thousands of years and can last hundreds of thousands of years. Because of this, clay minerals are essentially inert and usually do not undergo substantial chemical interaction with leachate.

Clays with a low permeability may be found in most of the world's areas and used for landfill containment [37]. Every one of these materials is routinely used in the construction of barriers within landfills. It is possible that the usage of clays will not be economically viable in areas where they are not readily accessible near dump sites. However, sands or coarse silts may be used with synthetic' clays, such as Bentonite, to generate a barrier with low permeabilities comparable to natural clays. Bentonite is a generic word that may refer to either calcium montmorillonite (Ca) or sodium montmorillonite (Na) [63].

5. An evaluation of the liners as attenuation

In addition to their low permeability, compacted clays can reduce the amount of pollutants in leachate through various processes [32,64,65]. These processes include sorption, dilution, redox transformations, biodegradation, precipitation, and filtering. According to [66,67], "attenuation" describes the quantity of environmental pollutants as reduced due to processes that occur independently without human intervention. These attenuation mechanisms happen concurrently and may affect more than one pollutant found in leachate. Pollutants may be attached to mineral phases or particulate organic matter by sorption, which can be either a physical or chemical process. Sorption comprises ion exchange, adsorption, absorption, and chemisorption, among other processes. Electron transfer processes may change organic and metal compounds into less poisonous or immobile forms. These transformations are called redox transformations.

Through biodegradation, microorganisms break down organic contaminants into their component chemicals [68]. The process of precipitation reduces the bioavailability or mobility of metallic contaminants. Because of filtering, more significant pollutants in the leachate, including metalorganic complexes, are kept inside the liner fabric rather than released. When it comes to chemical interactions, sorption, colloid filtration, and the transfer of pollutants, the surface of soil particles is critical. Clayey materials, in general, and Oxford Clay (OC), in particular, were found to have included particle organic matter (Table 1, Figure 5). This organic matter has a large surface area and a high CEC. Particulate organic matter is essential for reducing contaminant molecules, which it does by either sorbing them to its surface or encouraging the growth of microbial communities that would break down the pollutants into compounds that are less harmful or nontoxic.

The Critical Electron Concentration (CEC) in clay minerals and particulate organic matter is paramount for sorption. Clays can neutralize the negative charge caused by imbalanced substitutions of their structural cations by absorbing cations in the pore water. This process is known as sorption. Cationic contaminants in leachate can take the place of sorbed native cations. According to Griffin et al. [69], illites in all four clays have a high affinity for the selective sorption of NH4+ and K+. According to [70], smectites were more effective at adsorbing bigger cations, organic cations, or organometallic complexes in leachate than adsorbing smaller, inorganic, or uncomplexed metals. This was the case for all three types of species. This is the case because, for cations of the same valence, weakly hydrated cations are easier to sorb in the exchange sites than intensely hydrated tiny cations [71], and only smectites have an exchanger interlayer space that is wide enough to accept them. Smectite has a high CEC, as does vermiculite (interlayer magnesium), but illite has values in the middle of the range, and kaolinite has relatively low values. Therefore, the ability to lower the concentration of cationic pollutants in leachate via cation exchange processes follows the LC > OC > Coal Measures Clays sequence. CEC tends to rise along with pH due to accumulating a higher negative charge (the pH of leachate, on average, falls between 7-8).

The anion sorption process (which removes bicarbonate, chloride, and sulfate from leachate) is less effective for the various clay minerals (such as kaolinite and smectite) but is still relatively comparable. It occurs at OH^- ions exposed on the mineral edges and is exacerbated by positively charged iron-oxide colloids linked with clays [72]. These colloids may be found in London Clay (LC) and Coal Measures Clays. The amount of bicarbonate in leachate is the most critical factor in determining the acid-base neutralization potential of the system since it is the most abundant inorganic anionic component. This is beneficial for Coal Measures Clays, which do not have the pH buffering ability to attenuate acidic events, such as those generated by the oxidation of sulfides (pyrite) by rainfall infiltration [73]. According to [74], oxygenated water can re-oxidize sulfide phases, which may lead to the release of metals previously attenuated and precipitated earlier in such immobile phases.

For coal measure clays that lack calcite, bicarbonates in the leachate themselves would give them acid neutralization capability. The oxidation of pyrite in the higher, worn zone, which results in a low pH, gypsum, and amorphous iron oxides as by-products, is most likely what causes the acidity in Coal Measures Clays. In contrast to Na+ and the cations that are typically Ca^{2+} and Mg^{2+} replaced by NH^{4+} and K+ from the exchange sites of clays, chloride is not significantly attenuated and mainly diffuses through the clay liner [75,76]. Due to their low toxicity, even at very high concentrations, these elements are often not an issue and are diluted by the incoming groundwater. Anaerobic microbial reduction, a typical redox mechanism in landfills, attenuates sulfate in leachate [77]. Redox-sensitive species are present in the investigated clayey substrate, with pyrite in the OC and Shallow Coal Measures Clay (SCMC) and iron oxides in the LC, SCMC, and Deep Coal Measures Clay (DCMC) being the most significant examples. Consequently, the sulfate concentration in the leachate is relatively low, and the clays assist the metals in the liner in precipitating as sulfides.

The process of biodegradation is accompanied by changes in the redox potential of the waste, and it is these shifts that drive organic and inorganic species to go through reactions under a variety of aerobic and anaerobic conditions. According to [78], the specific redox conditions in the landfill and liner (aerobic, nitrate-reducing, iron-reducing, sulfate-reducing, etc.) determine whether or not one or more organic compounds may be biodegraded. This is the case even if aerobic conditions are present. According to [79], redox conditions may be deduced from the concentration of oxidizing agents and the reduced species produced by those agents in the leachate. The variances in clay minerals have less effect on the biodegradation of organic pollutants than their influence on the sorption of inorganic pollutants. Because only smectite, chlorite, and vermiculite would demonstrate considerable organic sorption to clay minerals, organic pollutants are predominantly attenuated by anaerobic biodegradation [78] [80,81], as opposed to sorption to clay minerals [78,80]. For organic compounds to be decomposed into water, methane, and carbon dioxide, the appropriate microbial population must first be formed. The OC, taken from a region rich in fossils, was found to have the highest concentration of organic materials, followed closely by the SCMC. According to [82], the native particulate organic matter of clay materials is necessary to maintain in-situ liners' biological activity. The microbial inoculum in the leachate also supports the liner's anaerobic decomposition.

The attenuation of heavy metals in leachate occurs due to a combination of three different processes: sorption, redox transformation, and precipitation [83]. These mechanisms are connected to particulate organic matter and mineral phases, including liner clay minerals. These processes are made more accessible by the presence of certain mineral phases [84]. These mineral phases include sulfate-bearing species (pyrite, gypsum), iron and manganese oxides and oxyhydroxides, and clays (mainly smectite and illite). Clay minerals are present in large amounts in all the materials under investigation, contributing to their ability to retain heavy metals. Pyrite can be found in the OC and the SCMC, while iron ore and metal oxides may be found in the LC, the SCMC, and the DCMC. While the organic molecules dissolved in the leachate make it more likely that soluble metalorganic complexes will form, the high native particle organic matter content of the OC makes it more likely that metals will get adsorbed to it. Even though metalorganic complexes are mobile and dissolved in leachate, filtration can reduce the concentration of these complexes [85,86]. However, some metals in the leachate complexed with dissolved organic matter or connected to colloids may not be reduced [73].

Table 1: Information about the samples of the natural clayey substrate

	Place (United Kingdom)	**Age**	**Where it all began**	**Appearance and coloration**	**Particular citations and sources**
London Clay (LC)	The north of Essex.	Eocene: 47.8 to 56.0 million years ago	sediments found at depth in the ocean	Brown hue that is consistent and robust	[87]
Oxford Clay from Peterborough Member (OC)	The northernmost parts of Buckinghamshire6.	164–166 million years ago, during the end of the Middle Jurassic.	sediments found in the ocean's depths	Carbonaceous shells and rootlets give this substance its grey appearance.	[87-89]
Shallow Coal Measures Clay (SCMC)	West Yorkshire, with samples taken from rather near to the surface	310 million years before now, in the Upper Carboniferous	sediments from fluvio-deltaic environments	Coloration ranging from dark grey to dark brown	[90,91]
Deep Coal Measures Clay, sometimes abbreviated as DCMC	West Yorkshire, gathered in more detail than ever	Upper Carboniferous: 310 million years ago	Dark grey-dark brown colour	310 million years ago, in the Upper Carboniferous.	[90,91]

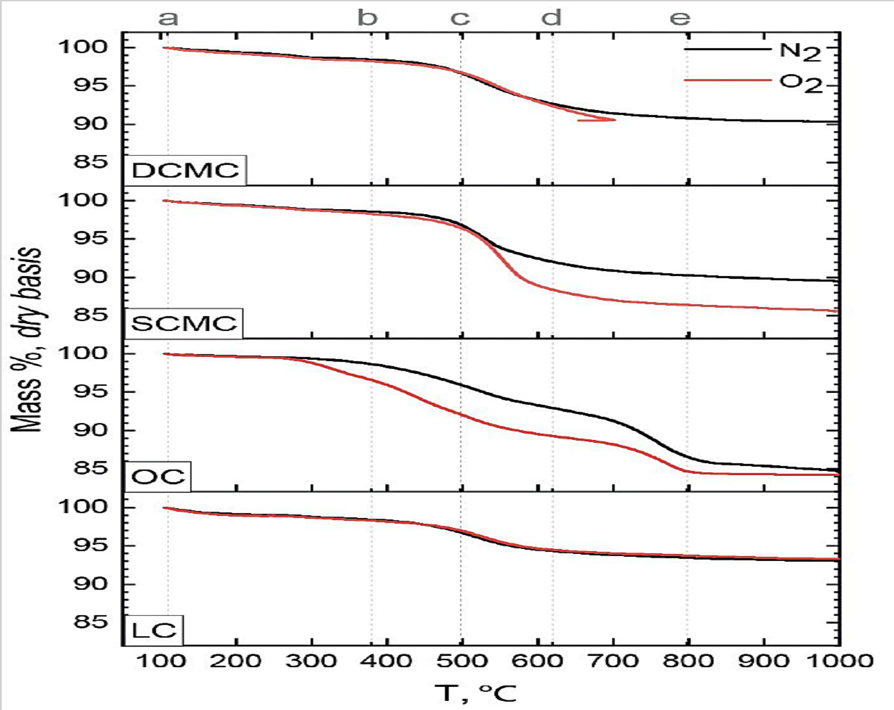

Figure 5: TGA curves show mass as a function of the mass after dehydration (the elimination of interlayer water) [67]

6. Liner alternatives

Table 2 briefly overviews some of the most common lining options, provides specific information for each liner, and provides estimated leakage (L) for each type. The projected leakage rates of various liners are also presented, and these rates are based on theoretical and real-world facts on the performance of landfills.

The following key ideas may be gleaned from the data shown in Table 2:

1) All the liners will dramatically reduce leakage compared to the case with no liner. A functional liner system is essential to a containment system design.
2) The quantity of leakage through the liner is at its lowest when "composite" liners are employed; in other words, liners with both a geomembrane component and a clay component give the highest performance now available.
3) The best performance is offered by liners containing both geomembrane and clay components. In a remark quite similar to the one that came before it, I said that a single-liner system, such as geomembrane alone or clay alone, etc., would not perform as well as a composite system. When attaining the lowest possible leakage values, the synergistic behavior of a geomembrane with a clay liner is critical. It should be taken advantage of whenever feasible.

Table 2: Different types of landfill liners and their related co ntainment abilities [92]

Type of liner	Liner information	Leakage estimate (lphd)	Comments
No lining	No liner. Prepared subsoils only. Subsoil permeability 1x 10-6 [cm/sec].	950000	The water table depth is estimated to be 3 metres.
Compacted clay lining(CCL)	permeability of clay = 1x10-9 [m/sec], thickness = 0.6m	1300	Based on Darcy's law research, it is exceedingly improbable that there will be any fractures or other losses.
Geomembrane	1.6mm HDPE laid on soil with 1x 10-6 [cm/sec] permeability	100 - 1000	The number of geomembrane holes or leaks is estimated to be 1 to 10 per hectare.
Geosynthetic Clay Lining (GCL)	Sodium bentonite encased by two geotextiles	860	Standard GCL steady-state flux under typical operating conditions
Clay Liner Made of Geosynthetic Membrane. (GCL)	Laminated geomembrane with two geotextiles around sodium bentonite	8.6	Estimated performance based on flow test results, with geomembrane taken into consideration.
GCL and geomembrane composite liners	Direct installation of geomembrane over GCL	0 - 4	based on real field data, an estimate of performance

The categorization of the research according to the kind of lining system is shown in Figures 6 and 7.

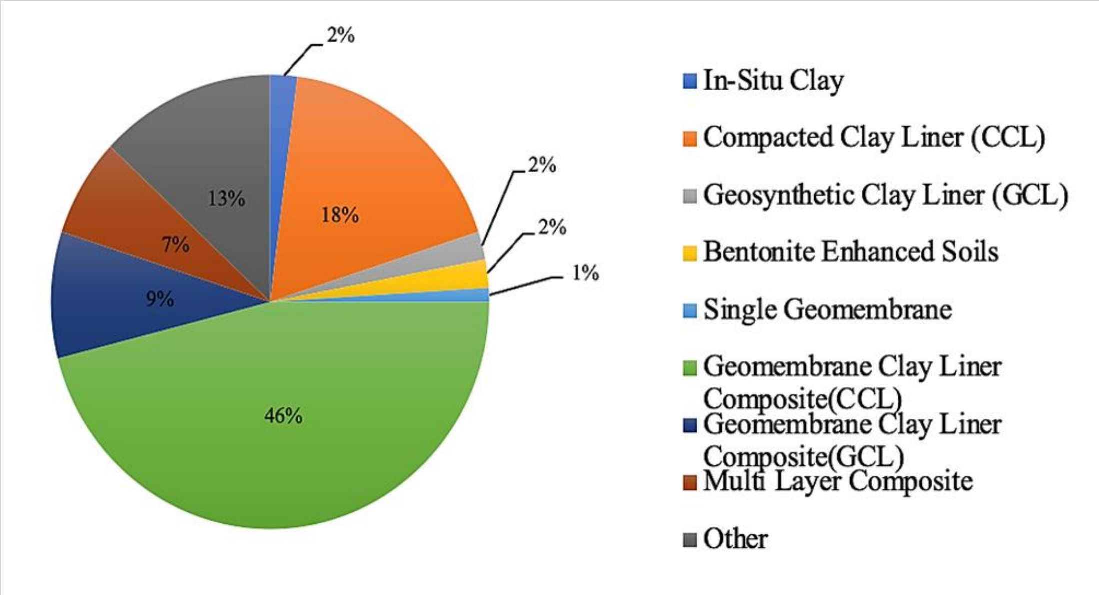

Figure 6: Classification of studies according to the type of lining system

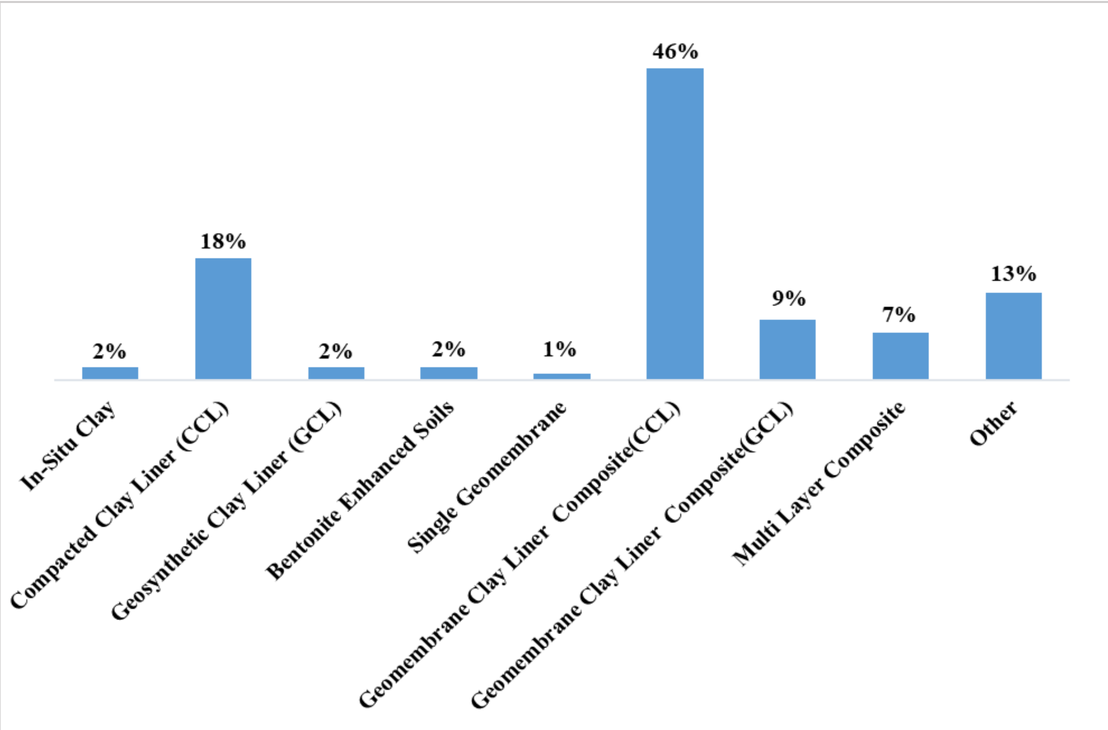

Figure 7: Statistical summary of the type of lining system

7. Geotechnical characteristics of the clay liner materials used in landfills

The practice of disposing of waste in landfills is considered to be the first technique of waste disposal. The term "bottom liner" refers to the essential component of landfills that is responsible for preventing leachate from moving down into the subsoil environment. A landfill liner must contain a precise range of swelling behavior, strength, and permeability before it can be placed under the created landfills. To provide the researcher and consultant with a clear delineation that may assist them in designing an environmentally friendly and acceptable landfill liner system, the details of the various materials and their viability that fulfill the requirements to be utilized as landfill liners are presented in table form. Various materials have been applied to enhance the geotechnical qualities of landfill liners. These materials include the dump's Bentonite, sand, fly ash, cement, charcoal, marine clay, lateritic soil, and geosynthetics. In the bulk of the study effort, numerous soils have been used as liner materials. Table 3 lists the geotechnical features of these diverse soils. Bentonite and fly ash were used in various amounts in the experiments conducted by Wasil [93]. In order to produce compacted landfill barrier layers, it was discovered that fly ash with 15% bentonite had a low hydraulic conductivity for use. It has been discovered that the maximum value of SiO_2 may be found in coal ash, which is 86% [94]. According to Giridhar and Dharani [95], the minimal permeability value in Quarry Dust with bentonite clay was 5.8×10^{-11} m/s. On the other hand, Devarangadi and Shankar noticed a higher permeability value.

Table 3: Various types of industrial waste, together with geotechnical factors used in the earlier study for the liner

		Parameter										
		Compaction		Atterberg limits								
Waste material	**The kind of soil**	**Max. Dry unit weight M.D.D (k/m^3)**	**Optimum water content. O.M.C (%)**	**Liquid Limit L.L.**	**Plastic Limit P.L.**	**Plasticity Index P.I.**	**Hydraulic Conductivity (m/s)**	**Permeability (cm/sec)**	**UCS (kPa)**	**Percentage of swell(%)**	**Shrinkage limit (%)**	**Ref.**
Fly ash	B	11.34	33.0	39	24	15		1.2×10^{-7}				[93]
RHA	Kaolinite]	19.3	31.6	33.2	24	9.2	-	2.12×10^{-9}	375.15		27.20]	[94]
QD	B, clay	16.3	20.4	48.9				0.58×10^{-11}		41	37	[95]
Silica fume	clay	16.42	20.4	42	19,5	22.5			42			[96]
	LS, B, Z	12	35	152	110	42		8.77×10^{-8}				[97]
	Clay, B, Silica fume	16.3	21.4	51.19	20.95	30.29		8.2×10^{-8}	241.31	7.8		[98]
MD	clay	16.5	19	42	33	9	9.8×10^{-10}		790			[99]
FA	Bentonite			62				30×10^{-9}	591			[100]
PA	B, S	17.8	22.5	79	27	52	2.13×10^{-11}		360			[101]
BAF	MC	15.4	13.31	111.8	26.03	85.77					67.94	[102]
FS, MS	B1, B2	16.	22.4	79	20	59					24	[103]
FA, C		13.77	20.4				1.2×10^{-9}					[104]
FA	B	15.2	17	61.2	33	28.2	–	1.55×10^{-8}				[105]
GGBS	B, C	15.6	20.0	200.27			6.13×10^{-7}		722.06	440		[106]
	Soil, B, nano-silica	10.2	62	131	100	31		8.68×10^{-8}	234.62			[104]
Geomaterials (tuff and calcareous sand)	B	16.8	14.3	35.54	24.07	11.47	1.83×10^{-10}		450			[108]
RHA	BEWFS	16.7	17	35	10	25	5×10^{-11}		454.2			[109]
Biochar (RHA)	Bentonite, M sand	16.8	18.3 %	52	37	15	6.50×10^{-10}		80			[110]
GGBS, cement	Bentonite, Laterite	16.8	18.40	42.11	21.48	20.63	$9.11\ 9 \times 10^{-10}$		669.84	100		[111]
Activated carbon	clay	16.7	18.3	43	25	18			400	14.5		[112]
Lime Silica - Fume mixture	clay	19.7	15.8	46	21	25	1.12×10^{-8}					[113]

Liners for landfills were constructed using a combination of bentonite and fly ash, as described by Kantesaria et al. [100]. The amount of bentonite in the combination is directly proportional to the rise in the observed liquid limit. By incorporating Bentonite at a level of up to 8%, it was shown that the soil mixtures exhibited an increase in both their strength and stiffness. Furthermore, it was discovered that the permeability decreased to a value below $1 \times 10^{-}$ m/s due to the increase in the percentage of Bentonite. Pal and Ghosh [102] performed the bottom ash clay mixes using various bentonite clay concentrations. Compaction, permeability, and hydraulic conductivity were some of the studied geotechnical factors.

Fly ash contains fifty percent bentonite clay. Srikanth and Mishra examined two different forms of sand, fine sand-bentonite and Medium Sand (MS)--bentonite [103], regarding their geotechnical properties. As the findings show, FS mixes exhibited higher liquid limits than MS counterparts, demonstrating that the change in liquid limit is not linear. The maximum dry density of FS mixes was low, and the ideal moisture content was much higher than average. As a result of the same amount of Bentonite, mixtures that included FS exhibited a greater swelling pressure and a poorer hydraulic conductivity. The impact of cement on the class F kind fly ash was the subject of research conducted by Mishra and Ravindra [104]. In addition to the fly ash, the quantities of cement employed were as follows: 0, 2, 5, and 10%. At OMC-MDD, every one of the compacted mixtures had hydraulic conductivities higher than the limitation value of 10^{-9} meters per second. Therefore, it was determined that fly ash combined with cement at a concentration of up to ten percent was not acceptable for use as a liner for a landfill. To analyze hydraulic conductivity and plasticity indices, Alla et al. [105] investigated the local soil in Sambalpur, Odisha (India), as well as fly ash and Bentonite mixes in varying amounts. The mix that contains the percentage of fly ash to Bentonite (85:15) and soil to Bentonite (95:5) demonstrates a downward trend in these parameters. Because of this, it was proposed that it be used as a material for the liner of landfills. Materials such as ground granulated blast furnace slag with Bentonite and cement mixture were used in the different experimental works conducted by Devarangadi [106]. These works included liquid limit, free swell index, unconfined compressive strength, and hydraulic conductivity. As the proportion of ground Granulated Blast Furnace Slag (GGBS) in the blends increased, the permeability of the blends dropped. According to the research, the optimal percentage of GGBS was recommended to be somewhere between 15 and 20 percent.

The characteristics of an updated landfill liner material were investigated by Nisha and colleagues [107] using a combination of site soil, nano-silica, and Bentonite. For the mixture consisting of 40% local soil, 30% bentonite, and 30% Nano silica, the coefficient of permeability values are 8.69×10^{-8} meters per second. Furthermore, as the amount of Bentonite and silica in the material increases, there is a significant drop in MDD and an increase in OMC, respectively. The research that was carried out by Demdoum and colleagues [108] included the use of three different materials, including Bentonite, as well as two other kinds of geomaterials, including tuff and calcareous sand, which is crushed sand. As a result of the compressibility behavior, the hydraulic conductivity exhibited a declining trend, which led to a rise in both the compressive strength and the tensile strength. Increasing the amount of calcareous sand increased shear strength. Ten percent bentonite, twenty percent calcareous sand, and seventy percent tuff were proposed as the ideal composition to meet the requirements of a landfill liner. To develop biochar that might be utilized as a liner material in the building of landfills, Cyrus et al. [110] carried out experimental work on biochar that was combined with bentonite clay and sand mixtures. Shankar et al. [111] discovered that the greatest value of Unconfined Compressive Strength (UCS) among ground granulated blast furnace slag and cement with Bentonite and Laterite clay was 669.84 kPa. This was the highest value of UCS. In the case of Bentonite, it has been discovered that the greatest percentage of swell is 5100 percent, while the lowest value of hydraulic conductivity is determined to be 1.3×10^{-11} m/s. The effect of adding different materials to reduce cracking due to desiccation and volumetric shrinkage in landfill lining soils prepared by adding Bentonite in small proportions was studied [114-116], as shown in Figures 8 and 9.

Figure 8: Photographs of the crack network developed in response to desiccation

Figure 9: Photographs of the drying stages to calculate volumetric shrinkage

8. Conclusions and future directions

The effectiveness of natural clay layers as potential landfill liners was evaluated by evaluating their physical and chemical properties, as well as their stability and leachability, after contact with leachate and then with rainfall. In leachate, contaminant dilution depends on the type of contaminant and the liner minerals. Regarding their content, toxicity, or persistence, the most representative leachate contaminants include potassium, ammonium, dissolved organic molecules, and heavy metals such as chromium, nickel, and zinc. All clays examined are beneficial for reducing leachate contaminants in environmentally responsible landfills.

Even though they have a relatively high potential to pollute the environment, landfills remain one of the most common waste disposal methods. This is even though unlined landfill sites have the potential to create a variety of environmental and health problems due to the generation of leachates from the wastes that are dumped over them, which is why the liners that are provided to them are so important after that comes the question of whether or not the liner materials are suitable and choosing them, since the beginning of the 1980s. Therefore, ongoing monitoring of landfills is necessary to detect and classify the risks that landfills provide to the surrounding ecosystem.

The most important future directions for studying landfill linings are summarized as follows:

1) Tracing the leachate flow at the pressure of municipal solid waste; this trace is made by placing sensors to measure the water content and temperature for distinct levels in a laboratory landfill for both rainy and dry seasons. The generated leachate will be sampled and monitored regularly.
2) An investigation of the variables that influence the value of water content, such as the state of stress in the soil, the kinds and quantities of clay minerals that make up the soil, and the types (species) and concentrations of the solutes that are present in the pore water
3) Studying the effect of clay liner layers as a barrier for decreasing the permeability rate in soil models. Experiments shall be carried out on soil models without geosynthetic clay liner layers. Then, the penetration experiments will be repeated with water and leachate on condensed soil models with geosynthetic clay liner layers.

This review paper on the existing literature demonstrates the importance of identifying knowledge gaps and laying the groundwork for developing a more comprehensive landfill risk assessment system. Studies are being conducted on this topic, and many people are still looking for the most effective solution, so putting it into practice would be more straightforward.

Author contributions

Conceptualization, K. Al-Soudany. M. Fattah and F. Rahil; data curation, K. Al-Soudany.; formal analysis, K. Al-Soudany. M. Fattah and F. Rahil.; investigation, K. Al-Soudany. M. Fattah and F. Rahil.; methodology, K. Al-Soudany.; project administration, M. Fattah and F. Rahil, resources, K. Al-Soudany.; software, K. Al-Soudany.; supervision, M. Fattah and F. Rahil.; validation, K. Al-Soudany, M. Fattah and F. Rahil.; visualization, M. Fattah and F. Rahil.; writing—original draft preparation, K. Al-Soudany. M. Fattah and F. Rahil.; writing—review and editing, , K. Al-Soudany. M. Fattah and F. Rahil. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

References

[1] Q. Tang, Y. Zhang, Y. F. Gao, F. Gu, Use of Cement-Chelated Solidified MSWI Fly Ash for Pavement Material: Mechanical and Environmental Evaluations, Can. Geotech. J., 54 (2017) 1553-1566. https://doi.org/10.1139/cgj-2017-0007

[2] Q. Tang, F. Gu, Y. F. Gao, T. Inui, T. Katsumi, Desorption Characteristics of Cr(III), Mn(II) and Ni(II) in Contaminated Soil Using Citric Acid and Citric Acid Containing Wastewater, Soils Found.,58 (2018) 50–64. https://doi.org/10.1016/j.sandf.2017.12.001

[3] Q. Tang, H. J. Kim, K. Endo, T. Katsumi, T. Inui, Size effect on lysimeter test evaluating the properties of construction and demolition waste leachate, Soils Found., (JGS). 55 (2015) 720-736. https://doi.org/10.1016/j.sandf.2015.06.005

[4] E. Q. Shehab, Z. B Mohammed and , M. Y. Fattah, Investigation of Characteristics Landfill leachate using Large Scale Lysimeter under Anaerobic Conditions, J. Univ. Shanghai Sci. Technol., 23 (2021) 70-82. http://doi.org/10.51201/Jusst12537

[5] T.L Zhan, C. Guan, H. J. Xie, Y. M. Chen, Vertical migration of leachate pollutants in clayey soils beneath an uncontrolled landfill at huainan, china: a field and theoretical investigation, Sci. Total Environ., 470-471(2014) 290-298. https://doi.org/10.1016/j.scitotenv.2013.09.081

[6] G.E. Blight, Graded landfill requirements in South Africa-the climatic water balance classification, Waste Manage. Res., 24 (2006) 482-490. https://doi.org/10.1177/0734242X06068516

[7] NBSC (National Bureau of Statistics of China), China Statistical Yearbook (in Chinese), China Statistics Press, Beijing, 2013.

[8] I.V. Sibiya, O.I. Olukunle, O.J. Okonkwo, Seasonal variations and the influence of geomembrane liners on the levels of pbdes in landfill leachates, sediment and groundwater in Gauteng province, south Africa, Emerg. Contam., 3 (2017) 76-84. http://dx.doi.org/10.1016/j.emcon.2017.05.002

[9] J. N. Hahladakis, A. Siddiqua, W. A. Al-Attiya, An overview of the environmental pollution and health effects associated with waste landfilling and open dumping, Environ. Sci. Pollut. Res. Int., 29 (2022) 18127-18139. https://doi.org/10.1007/s11356-022-21578-z

[10] A. A. Salem, Z. B. Mohammed, M. Y. Fattah, Leachate Properties of Municipal Solid Waste in Laboratory Landfill, Adv. Mech., 9 (2021) 143-150.

[11] R. K. Rowe and R. W. Brachman, Assessment of equivalence of composite liners, Geosynth. Int., 11 (2004) 273–286. https://doi.org/10.1680/gein.2004.11.4.273

[12] J. Hou, J. Li and Y.,Chen, Coupling effect of landfill leachate and temperature on the microstructure of stabilized clay, Bull. Eng. Geol. Environ., 78 (2019) 629–640. https://doi.org/10.1007/s10064-017-1099-z

[13] European Commission, Council Directive 1999/31/EC on the landfill of waste, Off. J. Eur. Comm'n., (O.J.E.C.), L 182 of 16.07, (1999) 26.

[14] G. Rajasekaran, K. Murali, S. Nagan, Amoudhavally, V., Santhaswaruban, V., Contaminant transport modelling in marine clays, Ocean Eng., 32 (2005) 175-194. https://doi.org/10.1016/j.oceaneng.2004.06.010

[15] G. Ozbay, M. Jones, M. Gadde, S. Isah, and T. Attarwala, Design and Operation of Effective Landfills with Minimal Effects on the Environment and Human Health, J. Environ. Public Health, (2021) 1–13. https://doi.org/10.1155/2021/6921607

[16] A.A. Al-Suraifi, Simulation of Contaminants Transport and Groundwater Flow for Basrah Landfill Site, Eng. Technol. J., P. A, 35 (2017) 560-570. https://doi.org/10.30684/etj.35.6A.2

[17] P.J. Fox, J.D .Ross, Relationship between NP GCL Internal and HDPE GMX/NP GCL Interface Shear Strengths, J. Geotech. Geoenviron. Eng., 137 (2011) 743–753. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000490

[18] H. Xie, C. Zhang, S. Feng, Q. Wang, H. Yan, Analytical model for degradable organic contaminant transport through a GMB/GCL/AL system, J. Environ. Eng., 144 (2018). https://doi.org/10.1061/(ASCE)EE.1943-7870.0001338

[19] K. Y. H. Al-Soudany, M. Y. Fattah, F. H. Rahil, A comprehensive review of new trends in the use of geosynthetics clay liner GCLs in landfill, Int. J. Intell. Syst. Appl. Eng., 11 (2023) 124-130. https://ijisae.org/index.php/IJISAE/article/view/2758

[20] H. Yan, H. Xie, H. Ding, D. Yang, C. Chen, Y. Chen, Y. Chen, Analytical solutio for one-dimensional steady-state contaminant transport through a geomembrane layer (GMBL)/compacted clay layer (CCL)/attenuation layer (AL) composite liner considering consolidation, Int. J. Numer. Anal. Methods Geéomeéch, 46 (2022) 1046–1063. https://doi.org/10.1002/nag.3334

[21] J. Qiu, L. Jiang, H. Pu, D. Song, M. Min, J. Tong, Analytical solutions for contaminant transport through a GMB/CCL composite liner system considering effective porosity and thermodiffusion, Comput. Geotech.,163 (2023) 105713. http://dx.doi.org/10.1016/j.compgeo.2023.105713

[22] F. Parastar, S. M. Hejazi, M. Sheikhzadeh, A. Alirezazadeh, A parametric study on hydraulic conductivity and self-healing properties of geotextile clay liners used in landfills, J. Environ. Manage., 202 (2017) 29-37. https://doi.org/10.1016/j.jenvman.2017.07.013

[23] H. Wu, Q. Wen, L. Hu, M. Gong, Z. Tang, Feasibility study on the application of coal gangue as landfill liner material, Waste Manage., 63 (2017) 161-171. https://doi.org/10.1016/j.wasman.2017.01.016

[24] E. Adar and M. S. Bilgili, The Performance of Four Different Mineral Liners on the Transportation of Chlorinated Phenolic Compounds to Groundwater in Landfills, Sci. World. J., (2015) 171284. https://doi.org/10.1016/j.wasman.2017.01.016

[25] Wei, Z., Shi, S., Shengwei, W., Haoqing, X., Xihui, F., Jianping, B., Fanlu, M,. Patent. Municipal solid waste landfill barrier system capable of prolonging breakthrough time of leachate and manufacturing method thereof, US2018016766 (A1), 2018.

[26] D. J. Kong, H. Wu, H. N., J. C. Chai, A. Arulrajah, State-of-the- Art Review of Geosynthetic Clay Liners, Sustainability, 9 (2017) 2110. https://doi.org/10.3390/su9112110

[27] R. K. Rowe, and H. P. Sangam, Durability of HDPE geomembranes, Geotext. Geomembr., 20 (2002) 77-95. https://doi.org/10.1016/S0266-1144(02)00005-5

[28] R. K. Rowe, H. P. Sangam, C. B. Lake, Evaluation of an HDPE geomembrane after 14 years as a leachate lagoon liner, Can. Geotech. J. NRC Canada, 40 (2003) 536–550. https://doi.org/10.1139/t03-019

[29] F. Louati, H. Trabelsi, M. Jamei, S. Taibi, Impact of wetting-drying cycles and cracks on the permeability of compacted clayey soil, Eur. J. Environ. Civ. En., 25 (2018) 696-721. https://doi.org/10.1080/19648189.2018.1541144

[30] N. Yesiller, C. Miller, G. Inci, K. Yaldo, Desiccation and Cracking Behavior of Three Compacted Landfill Liner Soils, Eng. Geol., 57 (2002) 105-121. https://doi.org/10.1016/S0013-7952(00)00022-3

[31] Allen, A., Containment landfills: the myth of sustainability, Eng. Geol., 60, 3-19, ASTM D 4318 Standard Test Methods for Plastic Limit of Soils, 2015 (American Standard).

[32] S. F. Thornton, D. N. Lerner, M. L. Bright, J. H. Tellam, The Role of Attenuation in Landfill Liners. Proc. Sardinia 93, 4th Int. Landfill Symp. (T. H. Christensen, R. Cossu, R. Stegmann, eds), CISA-Environmental Sanitary Engineering Centre, Cagliari, Sardinia, (2015) 407-416.

[33] S. F. Thornton, M. I. Bright, D. N. Lerner, J. H. Tellam, P. K. Scott, Laboratory studies of landfill leachate attenuation by clay liner materials, Proc. Sardinia 97, 6th Int. Landfill Symp. (T.H. Christensen, R. Cossu, R. Stegmann, eds), CISA-Environmental Sanitary Engineering Centre, Cagliari, Sardinia, (1997) 65-75.

[34] Beaven, R., Potter, H., Powrie, W., Simoes, A., Smallman, D., Stringfellow, Attenuation of organic contaminants in leachate by mineral landfill liners, Environment Agency, Integrated Catchment Science programme, Science report: SC020039/SR5 Project record, 2009.

[35] Kaza S., Yao Lisa C., Bhada-Tata P., Van Woerden F., What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. Urban Development, Washington, DC. ©World Bank, 2018.

[36] M. K. Widomski, W. Stepniewski, A. Musz-Pomorska, Clays of Different Plasticity as Materials for Landfill Liners in Rural Systems of Sustainable Waste Management, Sustainability, 10 (2018) 2489. https://doi.org/10.3390/su10072489

[37] C. F. A. Akayuli, S. S. R. Gidigasu, S. K. Y. Gawu, Geotechnical evaluation of a Ghanaian black cotton soil for use as clay liner in tailings dam construction, Ghana Min. J., 14 (2013) 21–26.

[38] A. solomon and E. Poulose, A Comprehensive Review on Landfill Liner, Int. Res. J. Eng. Technol., 5 (2018) 621-628.

[39] Department of the Environment , Waste management paper No 27. Landfill gas. HMSO, London, 1989.

[40] H. D. Robinson and J. Gronow, A review of landfill leachate composition in the UK. Proc 4th Int Landftll Symp, 11-15 Oct 1993, Sardinia, 1993.

[41] Y.-L..Yang, K. R. Reddy, T. Zhang, R-D. Fan, X.-L Fu, Y.-J. Du, Enhanced contaminant retardation by novel modified calcium bentonite backfill in slurry trench cutoff walls, Constr. Build. Mater., 320 (2022) 126285. https://doi.org/10.1016/j.conbuildmat.2021.126285

[42] EC directive on protection of groundwater against pollution caused by certain dangerous substances (1990). EC Directive 80/68/EEC, Commission of the European Communities, Brussels.

[43] I. Ahmad, N. Abdullah, S. Chelliapan, A. Yuzir, I. Koji, A. Al-Dailami and T. Arumugham, Effectiveness of Anaerobic Technologies in the Treatment of Landfill Leachate, Solid Waste Manage., 2020. http://dx.doi.org/10.5772/intechopen.94741

[44] A.N. Amadi, I.A. Okunlola, C.J. Eze, M.O. Jimoh, C.I. Unuevho, F. Abubakar, Geotechnical Assessment of Clay Deposits in Minna, North-Central Nigeria for Use as liners in Sanitary Landfill Design and Construction, Am. J. Environ. Prot., 3 (2015) 67-75.

[45] Christensen, T.H., R. Cossu, and R. Stegmann, Sanitary Landfilling: Process, Technology and Environmental Impact, London, Academic Press, 2012.

[46] Hughes, K. L., Christy, A. D., & Heimlich, J. E., Landfill Types and Liner Systems, Ohio State Fact Sheet, 2005.

[47] Yesiller, N. and C. D. Shackelford, Chapter 13: Geoenvironmental Engineering, Geotechnical Engineering Handbook, Edited by: B. M. Das, Fort Lauderdale, United States: J.Ross Publishing, 2010.

[48] Tchobanoglous, G. and F. Kreith, Handbook of Solid Waste Management, New York: McGraw-Hill, 2002.

[49] N. A. Jasim and J. A. K. Ibrahim, Stabilization of Al-Rustamiva Waste Water Treatment Plant Sludge Using Lime, J. Eng., 26 (2020) 165-172. https://doi.org/10.31026/j.eng.2020.09.11

[50] A. Allen, Containment Landfills: The Myth of Sustainability, Eng. Geol., 60 (2001) 3-19. https://doi.org/10.1016/S0013-7952(00)00084-3

[51] M. Ş .Özçoban, S. Acarer, N. Tüfekci, Effect of solid waste landfill leachate contaminants on hydraulic conductivity of landfill liners, Water Sci Technol., 85 (2022)1581-1599. https://doi.org/10.2166/wst.2022.033

[52] A. A. Salim, Z. B. Mohammed, M. Y. Fattah, Influence of adding plant fly ash on the geotechnical properties and pollution of sanitary landfill soil, Eng. Technol. J., 40 (2022) 1385- 1398. https://doi.org/10.30684/etj.2022.132687.1136

[53] T. Katsumi, C. H. Benson, G. J. Foose, and M. Kamon, Performance-Based Design of Landfill Liners, Eng. Geol., 60 (2001) 139-148. http://dx.doi.org/10.1016/S0013-7952(00)00096-X

[54] M. P. Patil, S. S. Quadri and H. Lakshmikantha, H., Alternative materials for landfill liners and covers, Guntur, IGC., (2009) 301–303.

[55] N. Hamdi & E. Srasra, Hydraulic Conductivity Study of Compacted Clay Soils Used as Landfill Liners for an Acidic Waste, Waste Manage., 33 (2013) 60–66. https://doi.org/10.1016/j.wasman.2012.08.012

[56] Zhou, P. Clay landfill liners subject to variable interfacial redox and pH conditions-heavy metal and clay interactions; LSU Doctoral Dissertations, 2003. https://doi.org/10.31390/gradschool_dissertations.3493

[57] G. Rajasekaran, K. Murali, S. Nagan, V. Amoudhavally, V. Santhaswaruban, Contaminant transport modelling in marine clays, Ocean Eng., 32 (2005) 175-194. https://doi.org/10.1016/j.oceaneng.2004.06.010

[58] Rowe, R.K., Quigley, R.M., Brachman, R.W.I., Booker, J.R., Rowe, R.K., Quigley, R.M., Barrier systems for waste disposal facilities, 1243-1243, 2004.

[59] H. Xie, C. Zhang, S. Feng, Q. Wang, H. Yan, Analytical model for degradable organic contaminant transport through a GMB/GCL/AL system, J. Environ Eng., 144 (2018). https://doi.org/10.1061/(ASCE)EE.1943-7870.0001338

[60] E. Kavazanjian, N. Dixon, T. Katsumi, A. Kortegast, P. Legg, H. Zanzinger, Geosynthetic barriers for environmental protection at landfills. Paper presented at the 8th International Conference on Geosynthetics, 8 ICG, Yokohama, Japan, 2006.

[61] F. Parastar, S. M. Hejazi, M. Sheikhzadeh, A. Alirezazadeh, A parametric study on hydraulic conductivity and self-healing properties of geotextile clay liners used in landfills, J. Environ. Manage., 202 (2017) 29-37. http://dx.doi.org/10.1016/j.jenvman.2017.07.013

[62] H. Wu, Q. Wen, L. Hu, M. Gong, Z. Tang, Feasibility study on the application of coal gangue as landfill liner material, Waste Manage., 63 (2017) 161-171.https://doi.org/10.1016/j.wasman.2017.01.016

[63] Y. Mohamedzein, A. Al-Ghaithi, M. Al-Aghbari, B. Tabook, Assessment of dune sand-bentonite mixtures for use as landfill liners, J. Solid Waste Technol. Manage., 42 (2016) 25-34.https://doi.org/10.5276/JSWTM.2016.25

[64] A. Allen, Containment landfills: the myth of sustainability, Eng. Geol., 60 (2001) 3-19. http://dx.doi.org/10.1016/S0013-7952(00)00084-3

[65] R. A. Griffin, N. F. Shimp, J. D. Steele, R. R. Ruch, W. A. White, G. M. Hughes, Attenuation of pollutants in municipal landfill leachate by passage through clay, Environ. Sci. Technol., 10 (1976) 1262- 1268. http://dx.doi.org/10.1021/es60123a006

[66] M. Regadío, A. I. Ruiz, M. Rodríguez-Rastrero, J. Cuevas, Containment and attenuating layers: An affordable strategy that preserves soil and water from landfill pollution, Waste Manage., 46 (2015) 408-419. http://dx.doi.org/10.1016/j.wasman.2015.08.014

[67] M. Regadío, J. A. Black, S. F. Thornton, The Role of Natural Clays in The Sustainability of Landfill Liners, Multi, Waste Resour. Residue., 12 (2020) 100-113. https://doi.org/10.31025/2611-4135/2020.13946

[68] Q. Tang, F. Gue, Y. Zhanga, Y. Zhangd, J. Mob, Impact of biological clogging on the barrier performance of landfill liners, J. Environ. Manage., 222 (2018) 44–53. https://doi.org/10.1016/j.jenvman.2018.05.039

[69] R. A. Griffin, N. F. Shimp, J. D. Steele, R. R. Ruch, W. A. White, G. M. Hughes, Attenuation of pollutants in municipal landfill leachate by passage through clay, Environ. Sci. Technol., 10 (1976) 1262-1268. https://doi.org/10.1021/es60123a006

[70] E. Koutsopoulou, D. Papoulis, P. Tsolis-Katagas, M. Kornaros, Clay minerals used in sanitary landfills for the retention of organic and inorganic pollutants, Appl. Clay Sci., 49 (2010) 372-382. https://doi.org/10.1016/j.clay.2010.05.004

[71] B. J. Teppen and D. M. Miller, Hydration Energy Determines Isovalent Cation Exchange Selectivity by Clay Minerals, Soil Sci. Soc. Am. J., 70 (2006) 31. https://doi.org/10.2136/sssaj2004.0212

[72] B. C. Raymahashay, A comparative study of clay minerals for pollution control, J. Geol. Soc. India, 30 (1987) 408-413.

[73] S. F. Thornton, D. N. Lerner, J. H. Tellam, Attenuation of landfill leachate by clay liner materials in laboratory columns: 2. Behaviour of inorganic contaminants, Waste Manag. Res., 19 (2001) 70-88. https://doi.org/10.1177/0734242X0101900108

[74] M. Regadío, I. S. de Soto, M. Rodríguez-Rastrero, M., A. I. Ruiz, M. J. Gismera, J. Cuevas, Processes and impacts of acid discharges on a natural substratum under a landfill, Sci. Total Environ., 463 (2013) 1049-1059. https://doi.org/10.1016/j.scitotenv.2013.06.047

[75] M. Regadío, A. I. Ruiz, I. S. de Soto, M. Rodriguez-Rastrero, N. Sánchez, M. J. Gismera, M. T. Sevilla, P. da Silva, J. Rodríguez-Procopio, J. Cuevas, Pollution profiles and physicochemical parameters in old uncontrolled landfills, Waste Manage., 32 (2012) 482-497. https://doi.org/10.1016/j.wasman.2011.11.008

[76] T. L. T. Zhan, C. Guan, H. J. Xie, Y. M. Chen, Vertical migration of leachate pollutants in clayey soils beneath an uncontrolled landfill at Huainan, China: A field and theoretical investigation, Sci. Total Environ., 470 (2014) 290-298. https://doi.org/10.1016/j.scitotenv.2013.09.081

[77] M. Batchelder, J. D. Mather, J. B. Joseph, The Stability of the Oxford Clay as a Mineral Liner for Landfill, Water Environ. J., 12 (1988) 92-97. https://doi.org/10.1111/j.1747-6593.1998.tb00155.x

[78] M. I. Bright, S. F. Thornton, D. N. Lerner and J. H. Tellam, Attenuation of landfill leachate by clay liner materials in laboratory columns: 1. Experimental procedures and behaviour of organic contaminants, Waste Manag. Res., 18 (2000) 198-214. https://doi.org/10.1177/0734242X0001800302

[79] R. Taylor and A. Allen, Waste disposal and landfill: information needs. In O. Schmoll, G. Howard, J. Chilton, I. Chorus: (Eds.), Protecting Groundwater for Health: Managing the Quality of Drinking-water Sources, London, 2006.

[80] S. F. Thornton, M. I. Bright, D. N. Lerner, J. H. Tellam, Attenuation of landfill leachate by UK Triassic sandstone aquifer materials 2. Sorption and degradation of organic pollutants in laboratory columns, J. Contam. Hydrol., 43 (2000) 355-383. https://doi.org/10.1016/s0169-7722(99)00105-9

[81] E. Adar, and M. S., Bilgili, The Performance of Four Different Mineral Liners on the Transportation of Chlorinated Phenolic Compounds to Groundwater in Landfills, Sci. World. J., (2015) 171284. https://doi.org/10.1155/2015/171284

[82] D. M. Martill, M. A. Taylor, K. L. Duff, J. B. Riding, P. R. Bown, The trophic structure of the biota of the Peterborough Member, Oxford Clay Formation (Jurassic), UK., J. Geol. Soc.,151 (1994) 173-194. https://doi.org/10.1144/gsjgs.151.1.0173

[83] C. A. Fannin, An evaluation of the chemical attenuation capacity of UK mineral liner and geological barrier materials for landfill leachate components, Q. J. Eng. Geol. Hydroge., 39 (2006) 267-281. https://doi.org/10.1144/1470-9236/04-073

[84] I. St. J. Fisher and J. D. Hudson, Pyrite formation in Jurassic shales of contrasting biofacies, Geol. Soc. London, Sp. Publ., 26 (1987) 69-78. https://doi.org/10.1144/GSL.SP.1987.026.01.04

[85] J. B. Christensen, D. L. Jensen, T. H. Christensen, Effect of dissolved organic carbon on the mobility of cadmium, nickel and zinc in leachate polluted groundwater, Water Res., 30 (1996) 3037-3049. https://doi.org/10.1016/S0043-1354(96)00091-7

[86] S.K. Gregson, R.D. Roberts, J.M. Roberts, The fate of heavy metals in co-disposed refuse, Environ. Technol. Lett., 9 (2008) 983- 990. https://doi.org/10.1080/09593338809384660

[87] C. A. Fannin, An evaluation of the chemical attenuation capacity of UK mineral liner and geological barrier materials for landfill leachate components, Q. J. Eng. Geol. Hydroge., 39 (2006) 267-281. https://doi.org/10.1144/1470-9236/04-073

[88] P. M. Scotney, J. B. Joseph, J. E. A. Marshall, M. J. Lowe, I. W. Croudace, , J. A. Milton, Geochemical and mineralogical properties of the Lower Callovian (Jurassic) Kellaways Sand, variations in trace element concentrations and implications for hydrogeological risk assessment. Q. J. Eng. Geol. Hydroge., 45 (2012) 45-60. https://doi.org/10.1144/1470-9236/11-005

[89] J. D. Hudson, and D. M. Martill, The Peterborough Member (Callovian, Middle Jurassic) of the Oxford Clay Formation at Peterborough, UK. J Geol. Soc. London, 151 (1994) 113. https://doi.org/10.1144/gsjgs.151.1.0113

[90] F. M. McEvoy, D. Minchin, D. J. G. Harrison, D. Cameron, E. J. Steadman, S. F. Hobbs, N. A. Spencer, D. J. Evans, G. K. Lott, D. E. Highley, Mineral Resource information in Support of National, Regional and Local Planning: West Yorkshire (comprising Metropolitan Boroughs of Bradford, Calderdale, Kirklees and Wakefield and City of Leeds), Commissioned Report, CR/04/172N (pp. 209): British Geological Survey, 2016.

[91] I. L.Freeman, Mineralogy of ten british brick clays, Clay Miner. B., 5 (1964) 474-486.

[92] Comparing Liner Types With GCL- ABG Geosynthetic, https://www.abg-geosynthetics.com/technical/landfill/comparing-liner-types-with-gcl/.\

[93] M. Wasil, Effect of bentonite addition on the properties of fly ash as a material for landfill sealing layers, Appl. Sci., 10 (2020) 1488. https://doi.org/10.3390/app10041488

[94] I. Arathy and J. Aparna Sai, Effect of pore fluids on some geotechnical properties of soil-rice husk ash mixture as barriers, Int. J. Eng. Res. Technol., 5 (2017) 1–4.

[95] V. Giridhar and S. Dharani, An experimental study on bentonite and quarry dust mixture to use as a landfill liner. SSRG Int. J. Civ. Eng. 5 (2018) 23–27. https://doi.org/10.14445/23488352/IJCE-V5I10P104

[96] K. Y. H. Al-Soudany, Remediation of clayey soil using silica fume, The 3rd Int. Conf. on Buildings, Construction and Environmental Engineering, BCEE3-2017 162, 2017, 01017. https://doi.org/10.1051/matecconf/201816201017

[97] S. Joseph and M. Varghese M, Study on amended landfill liner using bentonite and zeolite mixtures, Int. Res. J. Eng. Technol., 4 (2017) 1130–1133.

[98] N. Nambiar, N. Remya and G. K. Varghese, Effective reuse of waste material as an amendment in composit liner: assessment of geotechnical properties and pollutant retention capacity, Waste Manag. Res., 38 (2020) 134–141. https://doi.org/10.1177/0734242X19886920

[99] D. Devarajan and A. Sasikumar, Suitability of marble dust-soil composite as landfill liner material, Int. J. Eng. Res. Technol., 3 (2015) 1–6. https://doi.org/10.17577/IJERTCONV3IS29019

[100] Kantesaria, N., Chandra, P. and Sachan, A. Geotechnical behaviour of fly ash-bentonite mixture as a liner material.In: Proceedings of the Indian Geotechnical Conference; Lecture Notes in Civil Engineering, Springer, Singapore, 2021.

[101] S. Rout and S. P. Singh, Characterization of pond ashbentonite mixes as landfill liner material, Waste Manag. Res., 38 (2020) 1420–1428. https://doi.org/10.1177/0734242x20918013

[102] S. K. Pal and A. Ghosh, Hydraulic conductivity of fly ash–montmorillonite clay mixtures, Indian Geotech. J., 43 (2013) 47–61. https://doi.org/10.1007/s40098-012-0033-3

[103] V. Srikanth and A. K. Mishra., A laboratory study on the geotechnical characteristics of sand–bentonite mixtures and the role of particle size of sand, Int. J. Geosynth. Ground Eng., 2 (2016) 1–10. https://doi.org/10.1007/s40891-015-0043-1

[104] A. K. Mishra and V. Ravindra, On the utilization of fly ash and cement mixtures as a landfill liner material, Int. J. Geosynth. Ground Eng., 1 (2015) 1–7. https://doi.org/10.1007/s40891-015-0019-1

[105] V. Alla, S. K. Sasmal, R. N. Behera and C. Patra, Development of alternate liner material by blending fly ash, local soil and Bentonite. In: Indian Geotechnical Conf., 2017.

[106] M. Devarangadi., Use of ground granulated blast furnace slag blended with bentonite and cement mixtures as a liner in a landfill to retain diesel oil contaminants, J. Environ. Chem. Eng., 7 (2019) 103360. http://dx.doi.org/10.1016/j.jece.2019.103360

[107] S. L. Nisha and R. Roy, Design of amended landfill liner using nano silica, Int. Res. J. Eng. Technol., 5 (2018) 1438–1441.

[108] A. Demdoum, M. K. Gueddouda, I. Goual, H. Souli and M. S. Ghembaza, Effect of landfill leachate on the hydromechanical behavior of bentonite-geomaterials mixture, Constr. Build. Mater., 234 (2020) 117356. https://doi.org/10.1016/j.conbuildmat.2019.117356

[109] J. Ochepo, Effect of rice husk ash on the hydraulic conductivity and unconfined compressive strength of compacted Bentonite enhanced waste foundry sand, LAUTECH J. Civ. Environ. Stud., 5 (2020) 85–96. http://dx.doi.org/10.36108/laujoces/0202/50(0190)

[110] S. Cyrus, B. M. Abraham and B. T. Jose, Effect of partia replacement of Bentonite with biochar in liner soils, Biomass Convers. Biorefin., 13 (2021)1–9. https://doi.org/10.1007/s13399-021-01319-x

[111] D. C. Sekhar and S. Nayak, SEM and XRD investiga-tions on lithomargic clay stabilized using granulated blast furnace slag and cement, Int. J. Geotech. Eng., 13 (2017) 615–629. https://doi.org/10.1080/19386362.2017.1380355

[112] K. Y. H. Al-Soudany, A. Al-Gharbawi andM. Al-Noori, Improvement of clayey soil characteristics by using activated carbon, The 3rd Int. Conf. on Buildings, Construction and Environmental Engineering, 62, 2017, 01009. https://doi.org/10.1051/matecconf/201816201009

[113] M. Y. Fattah, Z. B. Mohammed and E. Q. Shehab, Enhancement of landfill clay liner properties using lime-silica fume mixture, SSRN, 2022. https://dx.doi.org/10.2139/ssrn.4200293

[114] S. Costa, J. Kodikara, S. L. Barbour, D. G. Fredlund, Theoretical analysis of desiccation crack spacing of a thin, long soil layer, Acta Geotech., 13 (2018) 39–49. https://doi.org/10.1007/s11440-017-0602-9

[115] C. J. Miller, H. Mi, N. Yesiller, Experimental Analysis of Desiccation Crack Propagation in Clay Liners. J. Am. Water Resour. Assoc., 34 (1998) 677–686. https://doi.org/10.1111/j.1752-1688.1998.tb00964.x

[116] Y. B. Yamusa, K. Ahmad, N. A. Rahman, Hydraulic conductivity and volumetric shrinkage properties review on gradation effect of compacted laterite soil liner, Malays. J. Civ. Eng., 29 (2017) 153-164. https://doi.org/10.11113/mjce.v29.15689