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Review

Geoenvironmental Engineered Structures for Water Protection: Challenges and Perspectives for Sustainable Liners

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Abstract: Geoenvironmental engineered barriers, such as geotechnical and hydraulic layered structures called liners, are essential for protecting the environment from pollution. Liners are usually compacted clay liners (CCL), geomembranes (GM), geosynthetic clay liners (GCL), or a combination of these liners (composite liners), which require significant attention concerning materials, techniques, and procedures to perform adequately. This work reviews the function of geotechnical and hydraulic barriers as liners and highlights the lack of investigation and problematic aspects of them. In addition, the work provides an overview of the literature around earthworks which are liners' specific configurations, such as landfills, dams, ponds, wastewater lagoons, and vertical barriers. Furthermore, the main investigations, issues, and perspectives are demonstrated, and are discussed alongside the trending research areas and sustainable new materials. This work highlights different directives in several countries for liner construction standards and testing program specifications, analyzing their economic aspects. The main studies on the subject have been compiled, and a bibliometric analysis was performed. Thus, this paper concludes by pointing out gaps in the research regarding alternative materials and structures within geoenvironmental investigations on liners, and signposts future scientific threads related to sustainable development.

Keywords: review; state-of-the-art; bibliometric analysis; liner material; compacted clay liner; geosynthetic clay liner; geoenvironmental engineering; hydraulic barrier; sustainable materials

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1. Introduction

Liners are structures that are used as containment barriers to prevent atmosphere, soil, superficial water, subsoil, and groundwater contamination [1] by pollutants that are released from landfills, dams, ponds, wastewater lagoons, dumpsites, among other sources. They usually consist of compacted clay liners (CCL), geomembranes (GM), geosynthetic clay liners (GCL), or a combination of those (composite liners), with the main purpose of environmental protection [2–5]. To prevent subsoil and groundwater contamination by pollutants infiltration, hydraulic conductivity (k) is the most significant factor for an assessment of liner performance [6].

The main requirements for liner materials are low hydraulic conductivity (usually k less than 10^{-9} m/s), chemical and environmental compatibility, low deformation during service, self-healing properties to avoid the occurrence of cracks or ruptures, and bearing capacity to support the surcharge of the disposed material [4,5]. Clays, like bentonite, emerge as the raw materials which best adhere to most of these requirements; however, depending on the region, the availability of such materials is scarce, generating high costs and constraints. GMs, and most notably GCLs, are materials with very low hydraulic conductivity. Furthermore, GCLs have good self-healing properties; however, they also may be expensive compared to CCLs, and they demand special construction control, and therefore compatible technical maturity, which is not available worldwide.

This justifies the need for researchers and practitioners to develop and investigate alternative materials, using other types of soils, feasible industrial waste, and mixtures of soil and waste. Besides good field performance, the associated environmental impact and socioeconomical aspects of these materials, along with the treatments and construction procedures they require, must also be investigated. Leachate from municipal solid waste (MSW), which contains harmful substances such as heavy metals, organic pollutants, and ammonia [7], may percolate through the soil and reach groundwater and/or nearby water bodies, impacting aquatic ecosystems and public health if the base liners have sealing problems. Leachate contamination processes include cationic exchanges, filtration, adsorption, complexation, precipitation, and biodegradation [8,9]. Dumpsites or inadequate MSW landfills lead to soil degradation and a loss of biodiversity in the surrounding areas due to pollution, reducing soil fertility, altering microbial communities, and causing changes in vegetation [10], disrupting ecological and natural processes. They also increase the fire risk due to the decomposition of organic waste and the release of flammable gases, which are allied to dry weather and elevated temperatures [11].

Furthermore, they may impact air quality by the emission of particulate matter and volatile organic compounds, causing respiratory problems to the nearby population [12]. An efficient cover, also built with liners, plays an important role in controlling greenhouse gas emissions, particularly methane, which is a gas with a much higher heat-trapping capacity than carbon dioxide (both are components of MSW biogas). Landfilling contributes approximately 20% of total methane emissions globally [13].

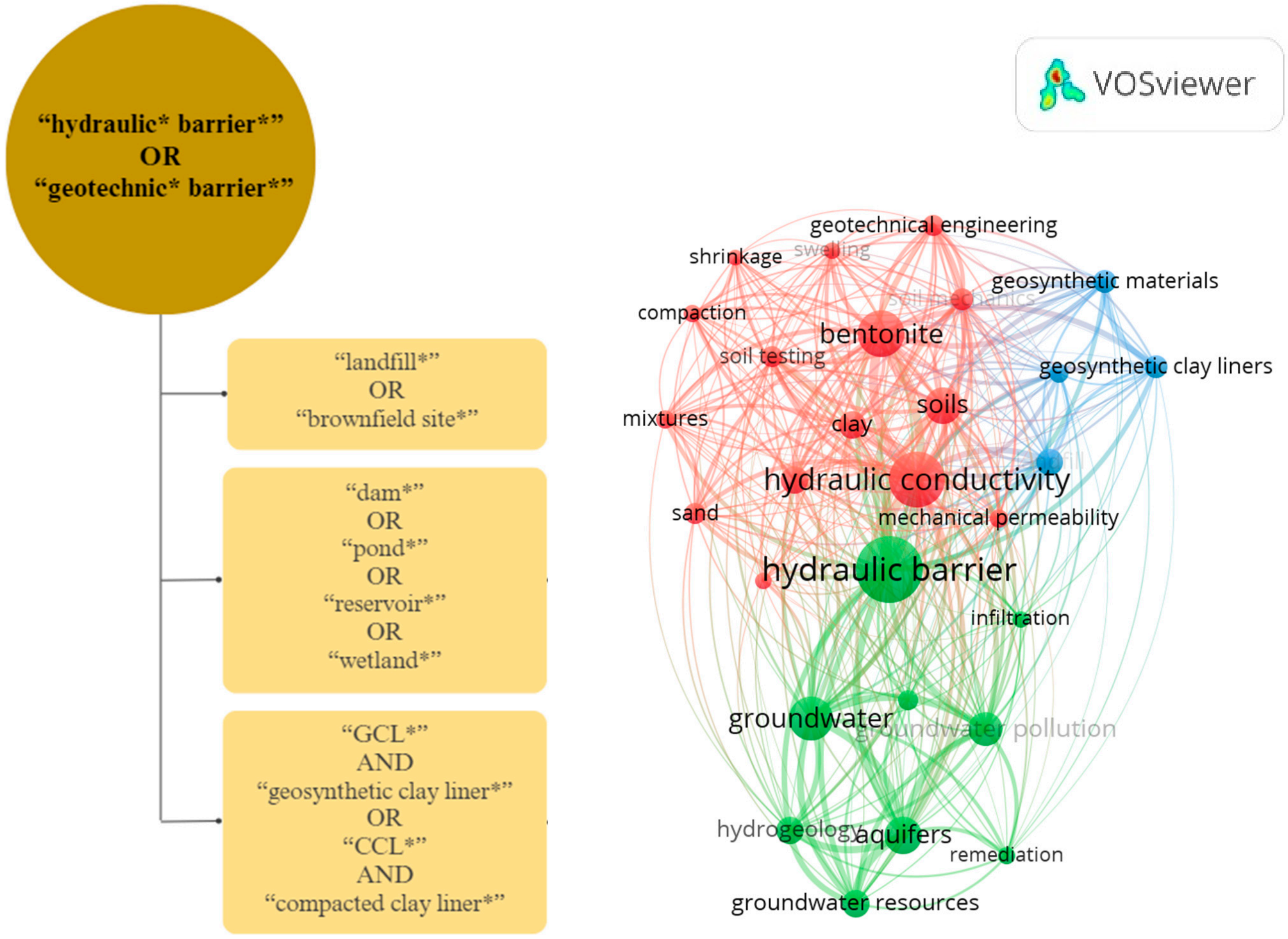
Recently, MSW landfills design has been performed by geotechnical engineers due to its technical and scientific contribution to hydro-mechanical properties and the site's operation, monitoring, and closure techniques [14]; however, there is still a lack of standardization and regulation in many countries. Waste management regulations are shaping the circular economy [15–17], and innovation has brought about transformative advancements, exposing the necessity of collaboration between researchers, policymakers, and practitioners. The integration of environmental and geotechnical engineering as a key innovation in waste containment and liners design has already been pointed out for circa three decades [18]. Presently, the integration of emerging technologies is essential to further refine waste management practices, and the implementation of sustainable practices based on waste treatment advancements and geotechnical performance of new materials can mitigate environmental impacts and safeguard ecosystems [19–22], facilitating sustainable waste management.

Thus, this paper aims to survey and study the literature on geotechnical liners acting as hydraulic and environmental barriers, pointing out the main contributions and opportunities for future sustainable practices, including innovative perspectives for new materials and structures.

The investigation on liners meets the United Nations (UN) Sustainable Development Goals (SDG) 9, 11, and 12 [23]. SDG 9 relates to industry, innovation, and infrastructure; research on alternative liner materials enhances sustainable infrastructure for waste containment, and the integration of industrial by-products as geomaterials promotes technological innovation. SDG 11 focuses on creating sustainable urban environments by ensuring proper waste disposal and contamination control. This research helps cities and communities to reduce soil and groundwater pollution by improving landfill and wastewater containment strategies. In addition, SDG 12 emphasizes sustainable consumption, waste reduction, and the circular economy. Thus, investigations on alternative materials, waste generation reduction, and valorization support these goals.

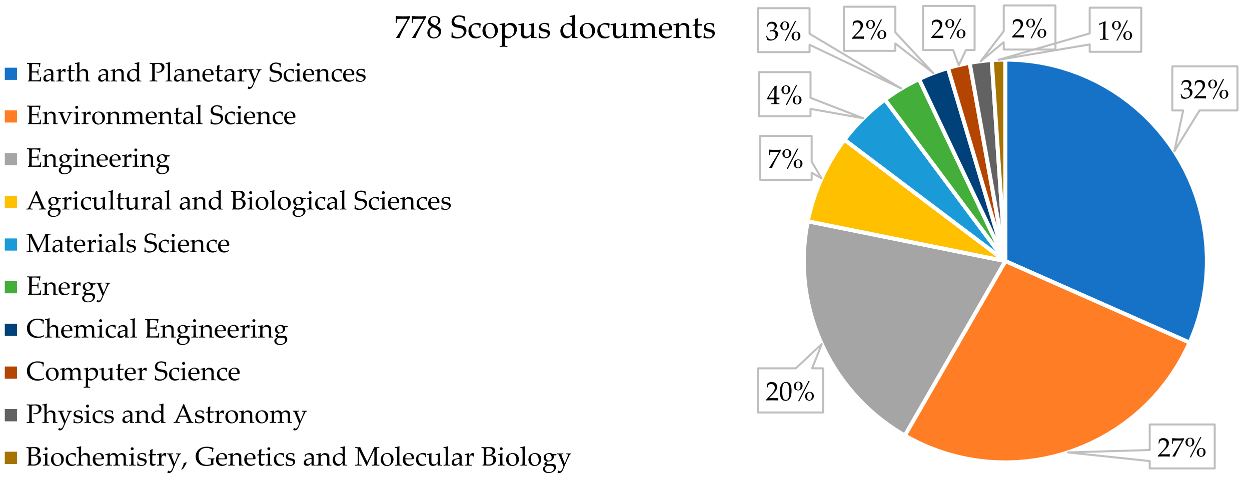
2. Bibliometric Analysis

The bibliometric analysis used the Scopus database, and the search was carried out with the following keywords, as shown in Figure 1a. The search started with "hydraulic* barrier" OR "geotechnic* barrier", resulting in 787 documents, then the research was channeled with separate keywords, "landfill" OR "brownfield site*"; "dam*" OR "pond*" OR "reservoir*" OR "wetland*"; "CCL*" AND "compacted clay liner*" OR "GCL*" AND "geosynthetic clay liner", generating 196, 118, and 127 documents, respectively. The papers were analyzed and then selected according to their relevance, and are listed in the references. Scopus' keyword co-occurrence when searching for "hydraulic* barrier" OR "geotechnic* barrier" data was exported, and the VOSviewer software (free, online software, version 1.6.20) was used to generate a keyword co-occurrence map (Figure 1b). Moreover, a pie chart with the research areas of the 787 works, and a graph showing the evolution of publications according to the year and country are shown in Figure 1c,d, respectively. In addition, Canva software (free, online resource accessed at https://www.canva.com/ (accessed on 29 January 2025)) was used to illustrate the flowchart (Figure 1a). To respect copyright and image rights, the artificial intelligence (AI) tool Imagine AI was used to illustrate the liners following the AIG identification, as shown in Figure 2.



(**a**) (**b**)

Figure 1. *Cont.*



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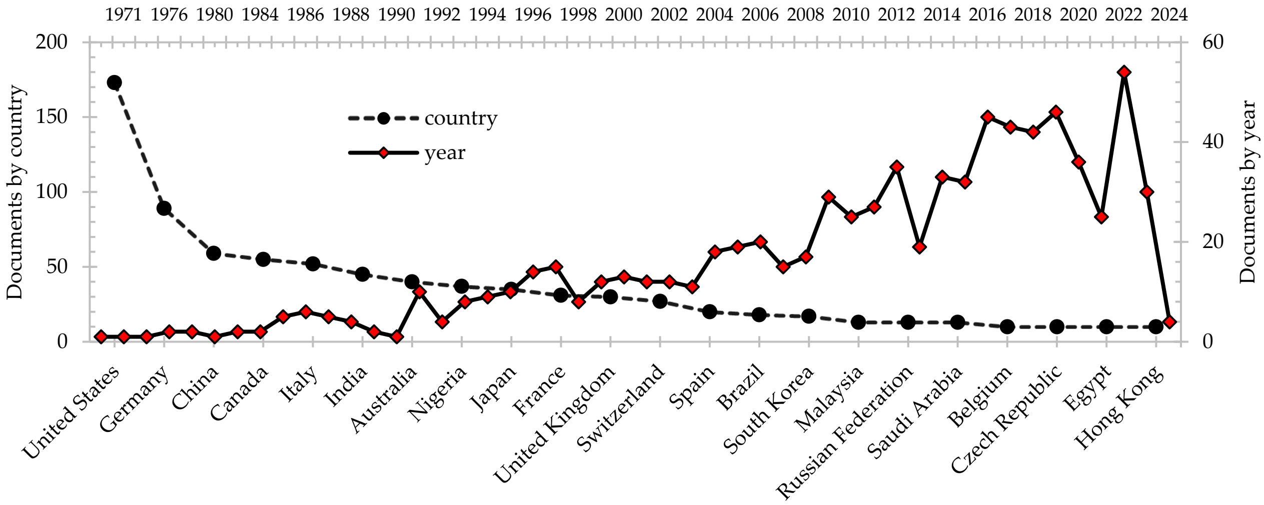


(**d**)

Figure 1. Bibliometric analysis keywords' research mechanism (**a**) co-occurrence map, (**b**) the main subject area chart, (**c**) year, and (**d**) countries of the 778 Scopus documents.

(**a**) (**b**) (**c**) (**d**)

Figure 2. AIG images of (**a**) a landfill, (**b**) an earth dam, (**c**) a wastewater lagoon, and (**d**) a dumpsite.

The keyword co-occurrence indicates that the strongest connections are among hydraulic conductivity, soils (clay), and geosynthetics (geomembranes and GCL). The red connections show geotechnical engineering concerns, with investigations into natural materials (bentonite, soil, sand, clay, mixtures), geotechnical properties (compaction, permeability), and problematic mechanical behaviors (shrinkage, swelling); the blue side expands that to geosynthetic materials; and the green one highlights environmental issues related to aquifers and groundwater (infiltration, pollution, resources, remediation).

Figure 1c shows that the studies on geotechnical and hydraulic barriers are concentrated, as expected, in the earth and environmental sciences (more than 50% of the studies); engineering is an important area, with 20%, followed by percentages equal or lower than 7% for agriculture, materials, energy, chemistry, computer science, physics, and the emerging subject of biochemistry. Figure 1d shows the increase in articles published during the past fifty years (red marker) and the number of papers released in each country (black marker), highlighting the huge scientifical and economic power, the United States of America, followed by the consolidated Germany, and the emerging player China, with more than 50% of all publications.

3. Waste Crisis

The world is facing a growing environmental crisis, which generates challenges for public health and sustainable development. The consequences of increasing population and exponential industrialization generate high amounts of waste, pollution, and contamination. Recent reports [24] have estimated that approximately 2.1 billion tons of municipal solid waste are generated annually, and this is projected to increase to 3.4 billion tons by 2050. This alarming quantity of waste poses a significant threat to our planet's ecosystems, human health, and economic stability.

The UN Environment Program (UNEP) [25] revealed that 54% of global waste consists of organic materials: 17% are paper and cardboard; 12% are plastics; 6% are glass; 5% are metals; 6% include other materials; and only 19% of MSW is currently recycled to make biogas, including paper, metals, and glass, in addition to plastics and treated biodegradable waste (by composting and anaerobic digestion). This average recycling percentage hides the huge differences in recycling among different countries. Oceanic pollution due to plastics not only harms marine life, but also enters the food chain, thus impacting human health, with an estimated 8 million tons of plastic being disposed in oceans every year [26]. So-called e-waste, or electronic waste, generated from technology activities presents health risks due to the presence of toxic metals like lead, mercury, and cadmium, and flame-retardant chemicals.

The main destination of all these kinds of residues is land disposal sites (Figure 2). MSW is mostly landfilled, despite the efforts in recent decades to find alternatives, such as incineration, composting, recycling, and valorization. The UNEP estimated that around 40% of landfilling worldwide is unsustainable, due to inadequate construction, management, or maintenance. Therefore, it is necessary to continue studying alternatives for waste reutilization and reapplication in geotechnical and civil engineering, or any other industry [27,28], as well as to improve the disposal of waste that will not be reutilized.

According to the European Waste Hierarchy [29], landfilling is not the most desired option and should be limited. In 2018, 24% of all municipal waste generated was landfilled, attracting attention to the effects on human health and on the environment because of bad construction methods [30]. In addition, the generation of leachate can contaminate groundwater and produce methane, a potent greenhouse gas [29]. This scenario, compounded by predictions that the world population will reach approximately 11 billion people by 2100 [31], means that the future regarding the storage and containment of waste must be addressed. Populations near waste sites that are not properly engineered can have severe health effects due to improper disposal and water, soil, and/or air pollution. In addition, exposure to toxic wastes cause can lead to respiratory and cardiovascular risks, among other issues [24]. Thus, these structures have the potential, when malfunctioning, to release pollutants, whereas proper MSW landfill design, construction, and monitoring may prevent environmental degradation and human health impacts [32]. In many underdeveloped and developing countries, where incineration is too costly and recycling and composting are still being implemented, well-engineered landfills are a reasonable solution for human health and environmental protection compared to mere waste dumping.

It is imperative to promote sustainable waste management practices, including waste reduction, recycling, and the adoption of modern landfill technologies. Economically, the World Bank reported costs reaching USD 450 billion per year by 2050 to ensure collection, treatment, and recycling, if no intervention is made [24]. Governments, academics, industries, and individuals must work together to implement sustainable waste management strategies, increase recycling rates, and promote responsible consumption, to mitigate the waste crisis and create a cleaner, sustainable, and healthier world for future generations.

4. Liners in Waste Disposal and Containment Facilities

Liners are a key component of storage facilities for waste and toxic substances, such as MSW landfills, mining tailing dams, wastewater ponds, fuel storage tanks, industrial storage tanks, disposal sites for drilling fluids, and heap leach piles, among others, since they protect subsoil and subterranean waters from spills, overflows, and leachates. MSW landfills and mining tailing dams stand out, since MSW landfills are still the most common destination for municipal solid waste all over the world, while mines and quarries are one of the biggest sources of solid waste [33]. According to the Mining, Minerals, and Sustainable Development Project [34], there are approximately 3500 active mining waste facilities worldwide, consisting of waste rock dumps and tailing dams [35].

Each application involves different specific pollutants, but the concept of minimizing the release of liquids and/or gases to the subsoil and/or atmosphere by means of a combination of drainage and impermeable layers is common to all of them. To approach the topic of liners, MSW landfills will be used as examples. Landfill disposal is based on the premise of confining or containing waste. Sanitary landfills are often disposal sites for urban waste, industrial waste is generally disposed of in industrial landfills, and mining tailings are stored in tailing dams or dikes, or in piles [32]. The classification of disposed waste (hazardous, nonhazardous) mainly depends on its composition. Modern regulations may prohibit the disposal of recyclable inert waste in MSW landfills (construction and demolition waste should have a specific destination to facilitate recycling), as well as hazardous substances that should have a reverse logistic, i.e., tires, pesticides, e-waste. Therefore, the components of MSW leachate and biogas may not significantly differ worldwide, despite the gravimetric composition (percentage by weight of each component) varying remarkably.

Important information regarding landfill design is the site climate, topography, geology and hydrogeology (including groundwater composition and seasonal variation), seismic history and rock geology, and the mechanical and hydraulic characteristics of adjacent soils for raw materials. Some design topics for landfill design are landfill construction modeling; subsurface drainage; bottom liner; waste compaction; daily, intermediate and final covers; run-on and run-off system; gas venting; leachate and gas collection and treatment systems; slope and foundation stability; in addition to long-term geotechnical and environmental monitoring [32,36].

The base and top control of a liner are the main geotechnical issues which should be addressed to minimize soil infiltrations and gas emissions, respectively, and waste compaction to optimize its capacity. Bottom liners and covers insulate the waste, bottom drainage layers remove the leachate, top drainage layers conduct the biogas to treatment or energy production, and the superficial drainage layers prevent surface erosion. Non-hazardous waste landfills' standards vary [37], but generally specify a bottom liner, mostly consisting of a soil layer with hydraulic conductivity less than 10^{-9} m/s, overlaid by a HDPE geomembrane, covered by a drainage layer. The geomembrane should be covered by an additional soil layer or a geotextile to protect against damage during the construction of the drainage layer [32]. Cover requirements differ according to regulations and authors' recommendations about soil classification [38], having at least 30–40% of the fine fraction, while the values of plastic index are between 10 and 50% [37,39,40]. Figure 3 shows a typical cross-section of a sanitary landfill adapted from [36], from the subsoil to the topsoil over the final cover for landscaping.

When in the presence of oxygen, the organic matter present in the landfill undergoes oxidation and decomposition; as soon as the oxygen decreases, anaerobic decomposition starts, first by facultative microorganisms, and later by methanogenic bacteria [41,42]. The product of water infiltration through the top and the decomposition liquid is named the MSW leachate, usually with a very complex composition, including chloride, nitrogen (ammoniacal, organic, nitrite, nitrate), phosphorous, heavy metals, high alkalinity, high BOD (biochemical oxygen demand), high COD (chemical oxygen demand), and a pH varying generally between 5 and 8 [43]. The estimation of leachate is based on the hydric balance of the cover system, landfill constituents, and construction characteristics.

The decomposition of organic matter generates the biogas, which varies along the biodegradation stages; during the longest stage, methanogenic, the main components are methane and carbon dioxide, both greenhouse gases [36]. Table 1 shows the major aspects and criteria for site selection. Groundwater conditions affect site selection; low usability aquifers are preferred. Additionally, the surrounding areas should be examined: proximity to lakes, rivers, and water courses that impact run-off and can be polluted must be avoided, as well as floodable areas, recharge areas, and drinking water supplies.

Table 1. Landfilling site selection criteria [44–46].

Aspect	Criteria	Impact	Preference
Topography	Cover	Sealing	Workability and k
	Slope	Release of contaminants	Lower than 15%
	Erosion	Migration of pollutants	Low erosion
	Run-on and -off	Leachate ratio	Little control needed
Soils	k	Release of pollutants	Low
	pH	Tendency to absorb HM	High-neutral
	CEC	Attenuate contaminants	High
	Surface	Protection and k for liners	Low k
Geology	Bedrock	Susceptible to fractures	Carbonated
	Joint	Discontinuity channels	Continuity

MSW landfilling demands urban areas, results in devaluation of the surroundings, and smells are still an inconvenience, even with gas collection and treatment. Nowadays, MSW landfills are being transformed into waste treatment centers, combining landfill for hazardous waste, recycling and composting areas, and desorption plants, among others, in the same site. Landfill mining [47] is an alternative strategy to help solve the lack of space problem and enhance circular economy, using treatment, recycling, and energy production from the mined waste; however, there are estimates that the reduction in the environmental impact is only around 28% [48].

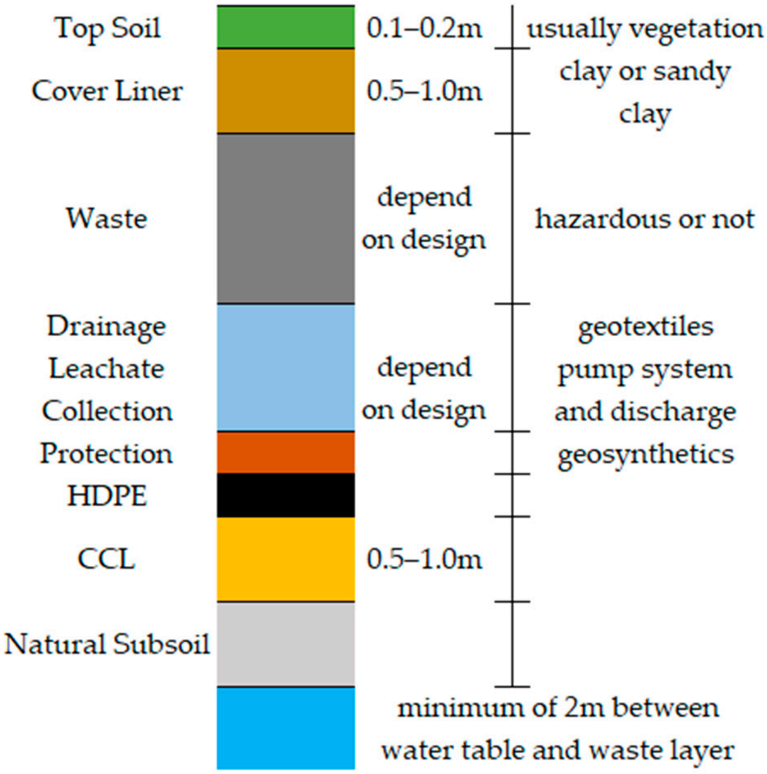


Figure 3. Typical cross-section, according to [44–46].

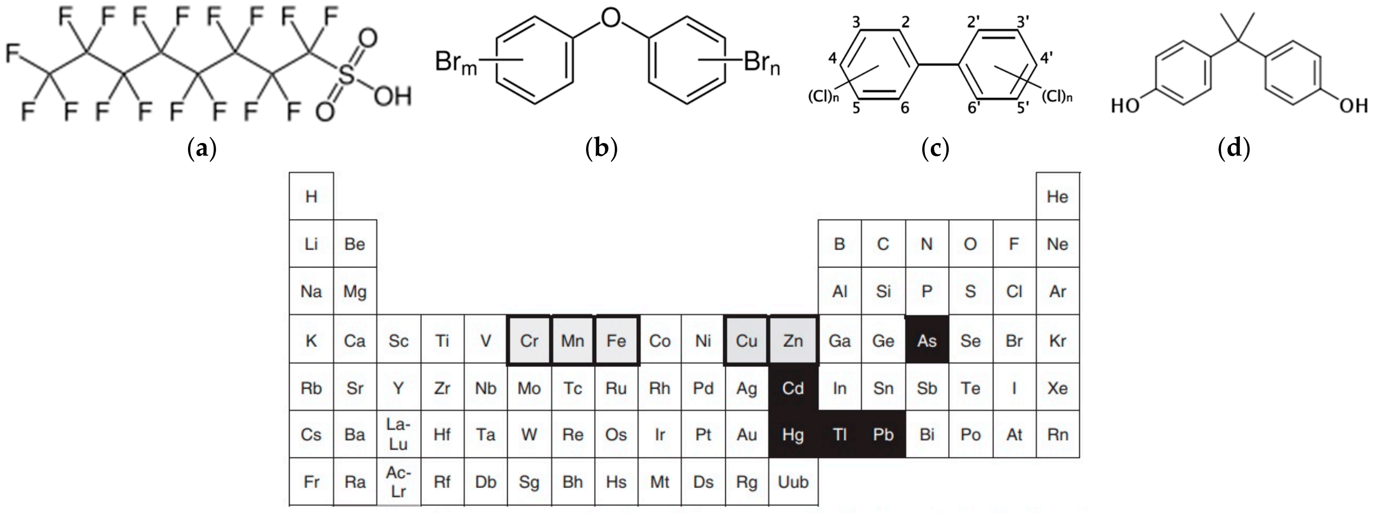
These technical measures significantly increase the construction costs of landfills and ponds, which can be a constraint in low-income regions. In 2016, landfill construction could cost from USD 300,000 to USD 800,000 per acre in USA, and the main impact is because of the availability of clay, ranging from USD 32,000 to USD 162,000 [49]. These costs undoubtedly vary significantly depending on the municipality, region, and country, but the MSW landfill is an engineered earthwork, requiring the costs that good design and construction demand. Site selection, operation, and closure are very important factors to study when investigating alternative materials for earthworks.

Regarding design parameters, there are numerous factors requiring consideration for landfill construction. Several works which provide an overview of many of these factors have been developed over the years; Refs. [50–58] are examples of some of these works developed in the 1990s and 2000s.

Unfortunately, in developing countries [9], dumpsites or non-engineered landfills are still predominant. However, researchers have recently provided promising solutions to remediate and redevelop brownfield sites, mainly risk assessment techniques monitoring the field [59], bioremediation using native microorganisms [60,61], or native grass species for the phytoremediation of heavy metal-contaminated soils [62]. In addition, the valorization of waste can help the redevelopment of brownfield sites to encompass principles of the circular economy [63]. This is emphasized by the importance of community engagement and social equity engaging stakeholders from government and industry to revitalize those sites [64], adopting a multidisciplinary and sustainable approach.

5. Key Contaminants

Among the key contaminants to be contained by environmental liners, heavy metals (HM) and the "forever chemicals", like per- and polyfluoroalkyl substances (PFAS), polybrominated diphenyl ethers (PBDE), polychlorinated biphenyls (PCB), and bisphenol A (BPA) [65], will be highlighted (Figure 4).



(**a**) (**b**) (**c**) (**d**)

(**e**)

Figure 4. Chemical structure of (**a**) PFAS, (**b**) PBDE, (**c**) PCB, (**d**) BPA, and (**e**) heavy metals harmful to humans in black, and toxic in large quantities in gray.

5.1. Forever Chemicals

PFAS are a group of synthetic chemicals that have alerted environmentalists' attention due to their persistence, bioaccumulation, and potential adverse health effects. Recent research has focused on their sources, effects, and remediation strategies. Reference [66] alerted the presence of PFAS in drinking water supplies, which has raised concerns about their adverse effects on reproductive, developmental, and immune systems. Reference [67] investigated the release of PFAS from textiles during washing. Other studies [68,69] have traced PFAS migration from landfills, industrial sites, and firefighting foams to the surface and groundwater, contributing to a better understanding of PFAS transport mechanisms. Analytical techniques in detecting and quantifying PFAS are crucial [69]; high-resolution mass spectrometry, isotopic dilution, and passive sampling methods are used in several fields. The persistence of PFAS in the environment has led to the development of remediation technologies: Ref. [70] investigated the use of activated carbon to remove PFAS from contaminated water sources; other innovative techniques, such as electrochemical treatment [60] and bioremediation [61], have also explored how to degrade or immobilize PFAS in the environment. Besides remediation, investigations on PFAS substitution in the industry is growing. Reference [68] reviewed the use of bio-based surfactants as substitutes for PFAS in firefighting foams, and highlighted their potential to reduce environmental impacts. PFAS regulation and risk assessment frameworks for guiding policymakers in establishing health-based exposure limits and managing PFAS-contaminated sites are still challenging governments for appropriate guidelines [71].

In addition, the PBDEs are a group of synthetic flame-retardant chemicals widely used at an industrial scale. Ref. [72] found a trace of PBDEs in surface water and sediments, proving that urban runoff and industrial discharge are their main pathway through the environment. Toxicologists and epidemiologists have investigated health issues caused by PBD exposure; neurological problems can impact particularly children during their development stages [73]. Analytical and accurate techniques have been studied to trace and quantify levels in various environmental samples, mainly using gas–liquid chromatography–mass spectrometry (GC-MS and LC-MS, respectively) [74]. Regulations and policies to control the use and disposal of PBDE are still in development, and are being discussed for environmental events [75], with a view to restricting the production and use of persistent organic pollutants, including certain PBDE congeners. There are already alternatives of flame retardants to replace PBDEs: Ref. [76] evaluated the effectiveness of organophosphate in consumer products and found promising results. In addition, remediation technologies are essential to address PBDE-contaminated sites; Refs. [77,78] investigated the effectiveness of advanced oxidation processes, such as photocatalysis and ozonation, for degrading PBDE in water and soil, and found promising preliminary results in mitigating the long-term impacts of PBDE contamination.

Another pollutant group is PCB, also recognized as persistent organic pollutants with harmful effects on human and environmental health. References [79,80] found PCBs in aquatic ecosystems analyzing sediment contamination. In addition, reference. Ref. [81] evidenced neurological cognitive impacts, which are especially worrying for pregnant women and children. GC-MS is used for PCB analysis, identification, and quantification [82], aiming to monitor contamination levels. In addition, chemical oxidation and phytoremediation seem to be effective remediation techniques [83] to degrade PCBs in soil and water. The Stockholm Convention on Persistent Organic Pollutants developed specific directives to control the production, use, and release of PCB [84], and [85] evaluated the environmental impact of alternative dielectric fluids in transformers to reduce PCB usage.

BPA has been used in the chemical industry for plastics and epoxy resins production over the years. Reference [86] demonstrated its endocrine-disrupting effects and BPA's impacting metabolic disorders. References [87,88] found high amounts in drinking water sources. LC-MS and GC-MS are already used for BPA detection and analysis [89]. Reference [90] investigated the use of bio-based polymers as alternatives to BPA-containing plastics, reducing the environmental burden. Regulatory efforts have led to banning BPA in some products, particularly those used by vulnerable populations, such as baby bottles and sippy cups [91]. Reference [92] is currently exploring analogs, which are structurally similar chemicals, to use as BPA replacements, without posing similar health risks.

5.2. Heavy Metals

HMs can cause poisoning, and are accumulated in soft tissues by ingestion, inhalation, or skin absorption. Figure 5 depicts health issues, detection and quantification methods, remediation techniques, and sustainable substitutes for the abovementioned contaminants.

The regulations outlined in Table 2 established the permissible limits for heavy metals in waste deposition across different regions, including the United States, China, and Europe, the latter continent for hazardous and non-hazardous waste. These regulations aim to prevent groundwater and soil contamination by ensuring that waste containment facilities maintain strict chemical compliance. A comparative analysis of different jurisdictions is provided, highlighting variations in environmental standards, within the maximum allowable concentrations (mg/L) of hazardous elements in the leachate, helping to determine the environmental safety of waste disposal sites.

Regarding the effect on the human body, arsenic (As), cadmium (Cd), lead (Pb), mercury (Hg), and thallium (Tl) are harmful, and some heavy metals, like zinc (Zn), copper (Cu), chromium (Cr), iron (Fe), and manganese (Mn), are required by the body in small amounts, but are toxic in larger quantities [93].

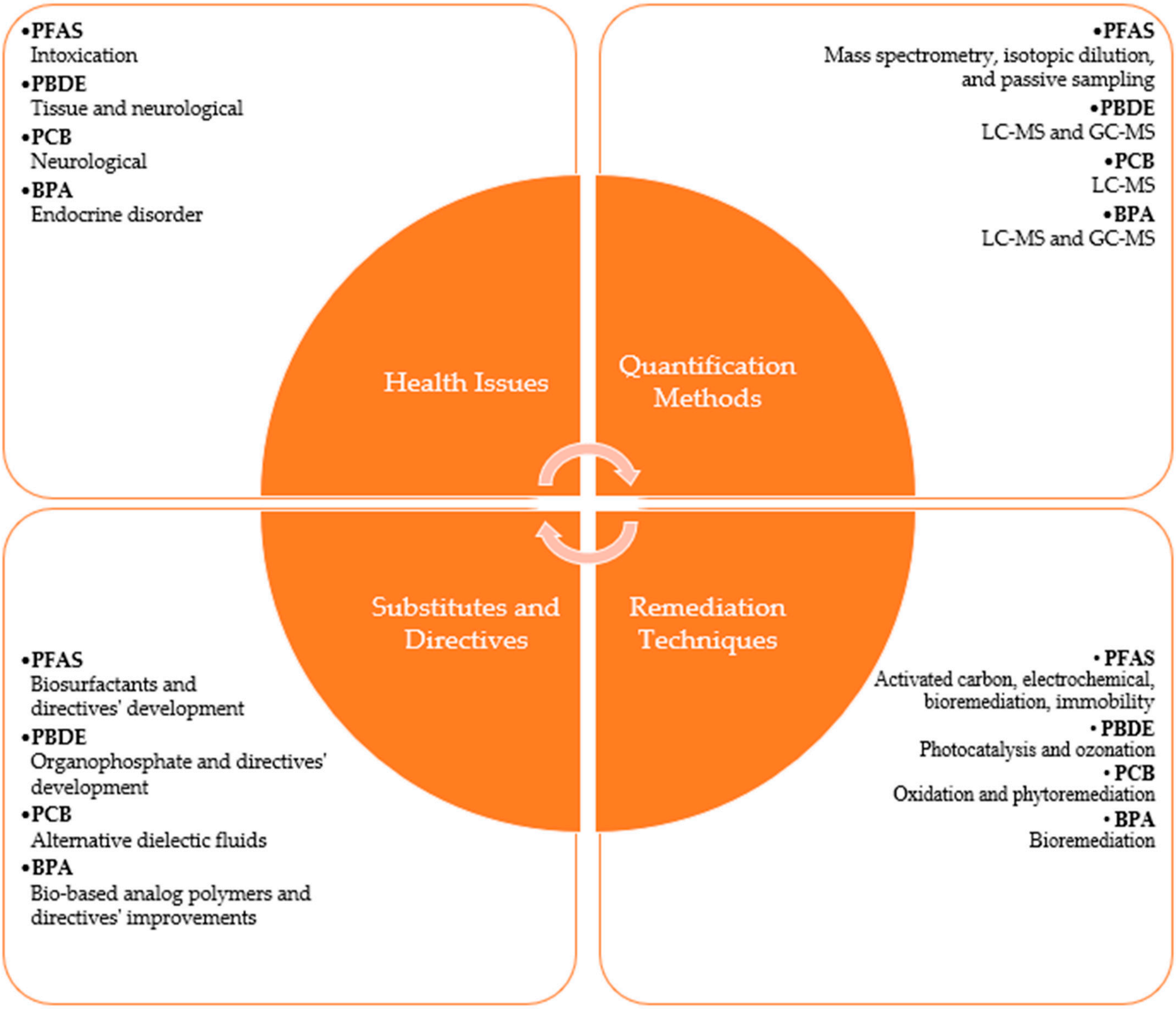


Figure 5. According to the literature, evaluation cycles for forever chemical contaminants.

Table 2. Heavy metals toxicity regulatory limits for waste deposition.

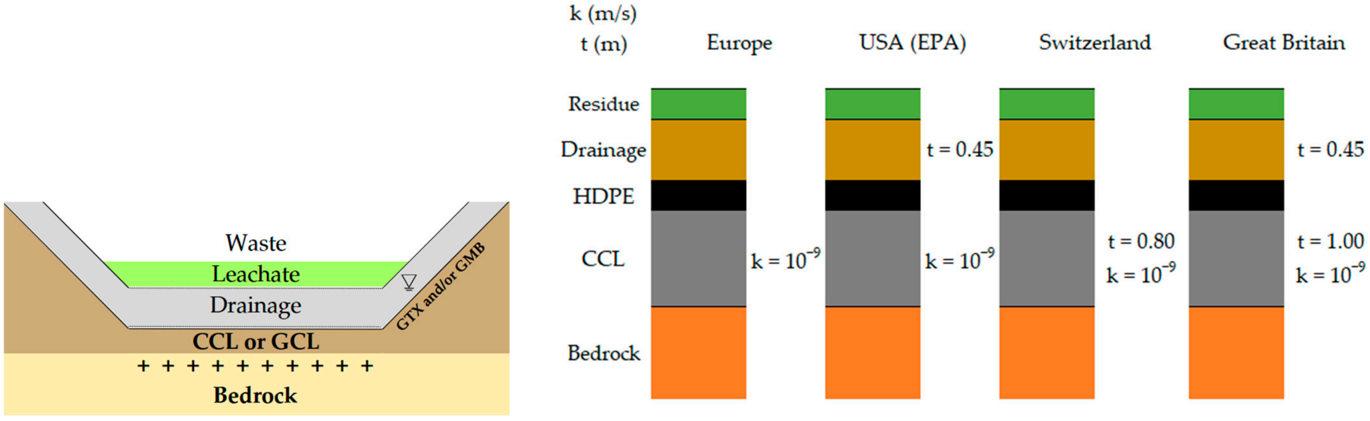
Heavy Metal (mg/L)	CFR 261.24 (2024) [1]	GB 5085.7 (2019) [2]	DL102 (2020) Hazardous [3]	DL102 (2020) Non-Hazardous [3]
Region	**USA**	**China**	**Europe**	**Europe**
Arsenic	5.0	-	25	2
Barium	100.0	-	300	100
Cadmium	1.0	1.0	5	1
Chromium	5.0	-	70	10
Copper	-	100.0	100	50
Lead	5.0	5.0	50	10
Mercury	0.2	-	2	0.2
Molybdenum				10
Nickel	-	5.0	30	10
Selenium	1.0	-	7	0.5
Silver	5.0	-	-	-
Zinc	-	100.0	200	50

[1] https://www.ecfr.gov/current/title-40/chapter-I/subchapter-I/part-261/subpart-C/section-261.24 (accessed on 25 January 2025); [2] https://www.codeofchina.com/standard/GB5085.7-2007.html (accessed on 25 January 2025) [94]; [3] https://eur-lex.europa.eu/eli/dir/2018/850/oj?locale=pt (accessed on 25 January 2025) [95,96].

6. Liners Materials

6.1. Compacted Clay Liners

Compacted clay layers may be used as bottom liners, to separate pollutants of the waste from the subsoils and groundwater, and/or covers, to separate waste from the atmosphere and superficial waters, ensuring sealing conditions and preventing environmental impacts [97]. They were widely used since the early 70s, and assumed an important role in landfill technology. Conventional CCL (Figure 6a) frequently contains bentonite [68], but other clayey soils have been used. The performance of mixtures of bentonites with other clays, silts, and sands has been investigated [14].



(**a**) (**b**)

Figure 6. Typical single-layer liner cross-section (**a**) and liner design's directives from different countries regarding k and thickness (t) (**b**).

The limit k value for CCL liner is generally 10^{-9} m/s [98], although this value can vary depending on local directives [32] (Figure 6). The main properties of soils which are used in liners to block pollutants migration [99] were summarized as follows:

- Very low hydraulic conductivity
- Strength to support the disposed material weight
- Deformation during service without failing or cracking
- Chemical compatibility with leachate
- Low-cost and easy construction materials
- Reference [38] exemplifies regulatory proposals for selection of materials
- Classification as low-to-medium plasticity; gravel, sandy, silty, and lean clays (CL); high-plasticity and fat clays (CH); clayey sands mixtures (SC); or medium-to-high plasticity clays (OH), according to the Unified Soil Classification System (USCS)
- Higher than 30% of particles passing 0.075 mm sieve (#200)
- Liquid limit (w_L) equal to or higher than 30%, and plasticity index (PI) equal to or higher than 15%
- pH equal or higher than seven and high cation exchange capacity (CEC)
- Maximum volumetric shrinkage of 4%

Table 3 shows the parameters used to characterize candidate materials for liner construction, and their corresponding laboratory or in situ tests.

Clays have low k when well-compacted, and are therefore natural candidate materials for barriers. However, they have been overexploited, and/or are not naturally available within reasonable distances from the earthworks. Furthermore, soils are natural resources that should be protected.

Table 3. Liners' main properties and parameters to be determined.

Aspects	Properties	Parameters
Physical Identification	Particle size distribution	Fines percentage, uniformity coefficient (Cu), curvature coefficient (Cc), specific surface (SS), and soil classification
	Physical index	Natural water content (w), specific gravity (Gs), void index (e), and saturation degree (s)
	Plasticity	Liquid limit (w_L), plastic limits (w_P), and plastic index (PI)
	Compaction	Optimal water content (OMC), maximum dry density (MDD), and relative compaction (RC)
Chemical Composition	Mineralogy	X-ray diffraction (XRD)
	Composition	X-ray fluorescence (XRF) for oxides, Fourier-transformed infrared (FTIR) for molecules bonds, and thermogravimetric analysis (TGA)
	Microstructure	Scanning electron microscopic (SEM)
	Adsorption	Cation exchange capacity (CEC)
Geotechnical Characterization	Expansibility	Free swell (FS), and swelling or shrinkage limits (w_S)
	Consolidation	Compressibility (C_C), recompression (C_R), swelling index (C_S), and consolidation coefficient (Cv)
	Shear strength	Cohesion (c), internal friction angle (φ), undrained shear strength (Su), and unconfined compressive strength (UCS)
	Hydraulic conductivity (k)	Permeability and acceptable compaction zones (ACZ)
Environmental Compatibility	Workability	Friction, tear, burst, and punching
	Climate	Wet–dry (W-D) and freeze–thaw (F-T) cycles
	Thermal	TGA
	Chemical	Leachability and solubilization
	Biological	Biocompatibility, bioclogging, and treatment

From a mineralogical perspective, CCLs consist of a clay layer, each composed of specific minerals which result in unique properties that affect liner performance. Kaolinite, aluminum silicate hydroxide $Al_2Si_2O_5(OH)_4$, is the main mineral of clays. Kaolin is a very important constituent in the production of ceramics, paint, plastic, and rubber materials. Kaolinite derives from the decomposition of feldspar by the action of water and carbon dioxide [100]. Its crystallographic structure consists of one sheet of silica tetrahedra combined with one sheet of alumina octahedra held by hydrogen bonding (1:1 mineral). The isomorphic substitution is low [101], so that kaolinite has a low swelling potential and liquid limit. Halloysite is also a 1:1 mineral related to kaolinite, except for its tubular form. Illite has a basic structure of one alumina sheet between two silica (2:1 mineral), linked by a weak bond of interchangeable potassium ions between the sheets; in the silica sheet, there is a partial substitution of silica for aluminum. Illite has moderate swelling potential and a higher liquid limit than kaolinite. Montmorillonite, a member of the smectites group, has the same crystallography structure as the illite, except that there are water molecules instead of potassium ions; an isomorphic substitution trivalent aluminum ion for a bivalent magnesium ion occurs in a 1:6 proportion, and has a very weak bond with water molecules and interchangeable cations. Montmorillonite has a large specific surface area that, allied to the high isomorphic substitution, favors the retention of positively charged and polar species [36,100,102,103]. Table 4 synthesizes some characteristics of kaolinite, illite, and montmorillonite that are relevant for the selection of materials for liner construction.

Table 4. Clay minerals' characteristics [100].

Clayey Mineral	Gs (-)	CEC (meq/100 g)	SS (m^2/g)	w_L (%)	w_P (%)	FS (%)
Kaolinite	2.6–2.7	3–15	10–20	30–60	25–35	10–20
Sodium				50	20	20
Calcium				40	10	10
Illite	2.6–3.0	10–50	65–100	60–120	35–60	15–20
Sodium				60	30	15
Calcium				90	40	20
Montmorillonite	2.3–2.7	80–200	700–900	100–900	50–100	80–250
Sodium				700	100	250
Calcium				200	60	80

Bentonite, a soil mostly composed of montmorillonite, has been extensively used in CCLs to retain MSW leachate pollutants [104]. It has a high swelling capacity and an extremely low k [100], and has been used in effective barriers for earthworks impermeabilization [105]. However, the degradation of bentonites generally occurs when permeated with acid solutions, such as those encountered in mining, affecting their physical properties [97]. Proper design and installation are needed to ensure the long-term integrity of the liner [106], like being well-compacted, pre-hydration, and in situ testing.

The performance of GCL and CCL can be affected by the type of bentonite used. Reference [107] tested BN (natural sodium bentonite) and BS (a sodium-activated calcium bentonite) permeated with distilled water (DW) and NaCl and $CaCl_2$ solutions. Very low k-values were achieved at an effective stress of 30 kPa; however, the values of k were higher with the permeation of the solutions, showing a detrimental effect on the hydraulic performance of both bentonites. BS generally has a lower hydraulic conductivity than BN when pre-hydrated with DW [108]. Not only does the type of bentonite affect the performance of GCLs, but the size of the grain: reference [109] tested a fine granular bentonite and a powdered bentonite, compacted on an optimal moisture and placed on a silty-sand layer. Powdered bentonite hydrated much quicker than the granular bentonite because of its higher specific surface, although both specimens achieved the same hydraulic conductivity along time.

Material science has led to innovations in modifying bentonite properties to enhance its containment efficiency. Reference [110] demonstrated that incorporating polymers can further reduce permeability and increase resistance to chemical interactions, contributing to more effective containment. Also, the use of numerical modeling and simulations to predict the behavior of bentonite liners under various scenarios has been investigated, such as different compactions or long-term effectiveness [111].

Enhanced bentonite liner (EBL) is another innovation in the field of geotechnical engineering which improved waterproofing and mechanical properties. Studies have focused on enhancing the performance of bentonite liners through innovative techniques and additives for environmental sealing [112–116], with permeability control [117] reducing the risk of failure. Their long-term durability under different leachate concentrations and temperature conditions and their compatibility with landfill leachates has also been investigated, ensuring their effectiveness in real-world scenarios [118,119]. The literature allied in situ and laboratorial testing within numerical modeling simulations for EBL [120], evidencing effectiveness in containing contaminants migration through soil and groundwater. EBL results in greater structural integrity, improved thermal conductivity, and the higher stiffness of the mixture [121].

Silty and sandy liners can also be applied as liners, despite needing optimized design. Bentonite–sand mixtures (BSM) are normally used in landfills, waste disposal facilities, and as CCL when the hydraulic conductivity of the local soil exceeds the allowable limit. Reference [122] evaluated the hydraulic conductivity of compacted bentonite–sand mixtures, which met the allowable limit values.

Reference [123] examined the k of enhanced sandy liners in landfill cover systems and found the importance of proper compaction techniques and material properties in achieving liner parameters, just like [105] for silty soils incorporating bentonite. In addition, Ref. [124] assessed geogrid-reinforced sandy liners on preventing contaminant transport and liner integrity through geotechnical conditions were advantageous. Among laboratorial and in situ characterizations of these soils, numerical simulations are also used to analyze the hydraulic behavior of compacted sandy and silty liners under different consolidation conditions [120], enhancing the understanding of liner behavior, especially for long-term performance and durability [125,126]. Reference [127] varied the clay percentage from

10 to 70% of clay content, and also the compaction energies, using reduced, standard, and modified, to test soils as landfill liners, and concluded that it is possible to reach minimum k by choosing the compact energy well.

Furthermore, silty clays and silts reached k values for liners, meeting directives from several countries. Some recent works about other soil types and bentonite mixtures must be mentioned: marine clay [128], lateritic [129], and saprolitic soils [14], and local soils mixed with bentonite [130].

6.2. HDPE

HDPE liners have become, among geosynthetic engineering, one of the most used and essential materials for barriers with diverse applications [131]. Durability, chemical resistance, and the impermeability of HDPE are the key components in environmental protection and waste management when obtaining attention for design and installation. The long-term mechanical properties of HDPE liners in a landfill cover system have been studied [132–134], and when reinforced with geogrids [135], they have tensile strength and stability which is crucial for maintaining integrity and the main issues of HDPE. In addition to the evaluation of different welding techniques on the shear strength of HDPE, the use of geomembranes [136]; slope stability [137], UV exposure and temperature fluctuations [138], and numerical modeling to predict HDPE performance [139] has been investigated over the past decades. Polymers and additives such as carbon black, titanium dioxide, antioxidants, hindered amine light stabilizers (HALS), and acid neutralizers, also need attention for their loss during service. Despite this, Ref. [140] showed that mechanical damage due to repeated loading and abrasion affected the k of geosynthetics and decreased tensile stress.

Enhancements in HDPE properties have been used for extreme situations and exposure to severe contaminants. An example of this is polyethylene with raised temperature resistance (PERT) resins due to efficient waste management. PERT resins, which exhibit enhanced temperature resistance compared to conventional polyethylene, make suitable for high-temperature environments [141], emphasizing sustainability and circular economic principles. In addition, Ref. [142] demonstrated that recycled geomembranes can offer comparable performance to virgin materials on durability and resistance under various conditions [143] among mechanical and thermal properties [144]. Reference [145] applied and studied HDPE as a cover liner and observed an increase in methane uptake flow, showing its importance in the capture of biogas.

Many studies have focused on HDPE geomembranes, not only as cover liners, but as basal lines when in contact with CCL, just like bentonite sand mixtures. Reference [121] analyzed the shear behavior at the CCL-HDPE interface under F-T cycles, a very important criteria for places with low temperatures. This analysis used sodium bentonite at a ratio of 1:10 in CCL and natural silica sand, such as the HDPE with 1.5 mm thickness, and showed that the shear behavior and resistance at the interface are affected by the number of F-T cycles, and the friction angle decreases together with the shear resistance from the first five cycles. Reference [52] noted that the geomembrane's temperature has a great influence on landfill's behavior, having a significant effect on the clogging rate of the leachate collection system. A wide temperature range was reported, from 5 to 25 °C, although higher temperatures, 50–70 °C, are mainly often attributed to aerobic conditions; however, the generation of gases, like CO_2 and CH_4, evidenced anaerobic conditions. The leachate percolation among membrane layers contains nutrients resulting in bacterial growth, principally in geotextiles filters, drainage layers, and collection pipes. This bacterial activity is called biological clogging [131]. Clogging phenomena involve the filling of the void space between solid particles as a result, not only with bacteria, but also a combination of biological, physical, and chemical factors [146–148], leading to a problem, although this can be controlled by an appropriate design, and it is important not to assume that clogging would make it waterproof.

Bituminous high-density polyethylene (BHDPE) is another alternative liner material which combines the durability and impermeability of HDPE with the enhanced sealing properties of bitumen, and has gained substantial attention for its potential to provide environmental sealing effectiveness. It is widely used for hydraulic infrastructures for geotechnical and environmental protection [149]. Its advantages are basically mechanical and hydraulic properties [149], preventing fluid migration and diffusion of hazardous substances [150]. Despite this, UV radiation and cyclic temperature changes can impact their performance [151], showcasing the importance of case studies and field monitoring in a hazardous waste containment site [152] integrated with numerical modeling to predict the behavior under stress distribution [153,154]. Reference [149] studied the interface transmissivity between GCL with sodium and calcium bentonite and smooth or textured HDPE. The results concluded that it can fit for hydraulic barrier design regarding chemical and mechanical compatibility; furthermore, Ref. [155] found that pre-hydration increases flow rate and higher confining stress decreases it in small, intermediate, and large-scale experiments.

6.3. Geosynthetic Clay Liners

Geosynthetics have been utilized in civil engineering earthworks for separation, filtration, drainage, reinforcement, and barriers, for at least 50 years. Physical, chemical, and mechanical properties were highly tested, and standards have been improved during those years showing more effectiveness than natural products, clays, when acting as barriers for environmental protection. Some researchers have been investigating several raw materials, properties, tests, and standards of geosynthetics, providing vast knowledge for quality applications for each case [3,109]. However, on the economic side, geosynthetics have a higher cost of production compared with natural resources, and generates more waste in its production and installations. Depending on the dimensions and applied case, different types of polymers can be used, classified according to their mesh structure and properties, such as permeability, compatibility with clays, shear strength, puncture, self-healing properties, high temperatures, creep, freeze–thaw, and wet–dry resistance.

Geosynthetics, which are widely used for the impermeabilization of soil structures [156], can be made of natural materials—animal, vegetable, or mineral—or have a chemical origin—organic or inorganic [99]. The natural ones, coming from animals, are wool and silk, and the mineral ones are asbestos, besides those of vegetal origin, like jute, cotton, linen, and hemp. Chemical raw materials are divided into organic—natural and synthetic—polymers, and inorganic—glass, metal, and carbon. In general, the base polymers used in the manufacture of geosynthetics are polyesters, in particular polyethylene terephthalate (PET); polypropylenes (PP); chlorinated polyethylene (CPE); polyvinyl chloride (PVC); chloro-sulfonated polyethylene (CSPE); polyamide (PA); and the polyethylene, which is the most utilized in hydraulic barriers (PE), including very low density (LDPE), medium density (MDPE) and high density (HDPE).

Geosynthetics have several functionalities. For earthworks the main ones are reinforcement, separation and/or filtration, drainage, and fluid barriers, among others like protection, absorption, insulation, screening, containment, cushioning, surface stabilization, and vegetation reinforcement [157]. Figure 7 [158] shows the types, their use, and their respective functions, as summarized by [3]: geogrids for slope reinforcement beneath the waste and reinforcement for cover soils above geomembranes; geonets, for in-plane drainage; geomembranes (GMB), which are relatively impermeable as liquid and gases barriers; geocomposites (GCO), two or more geosynthetics for separation, filtration, or drain-age; geopipes, for rapid drainage systems and facilitating the collection of the leachate; geotextiles (GTX), for filtration and the geomembrane's protection from punctures; and geosynthetic clay liners (GCL), composite materials consisting of bentonite and geosynthetics used as hydraulic barriers and waterproofing materials preventing soil infiltration.

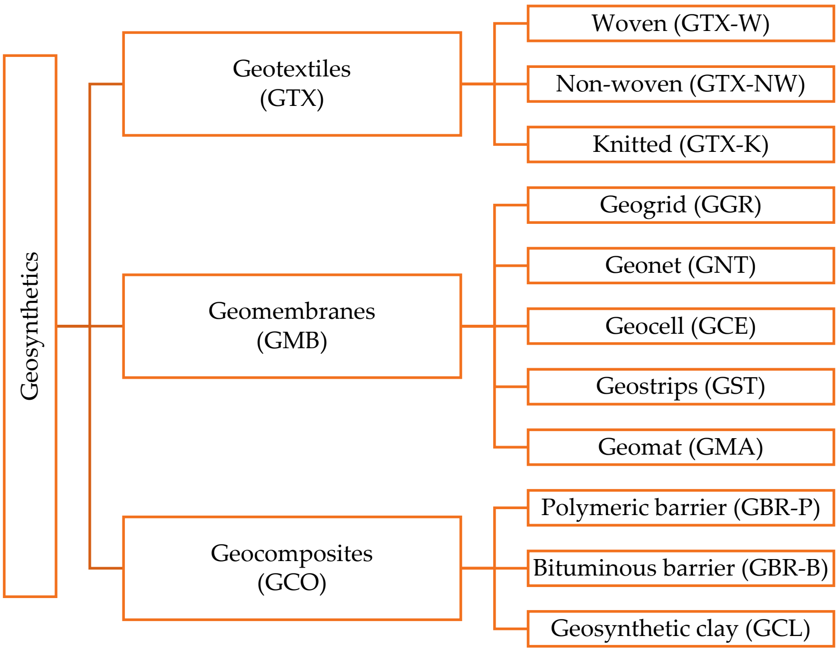


Figure 7. Geosynthetic types and acronyms.

After understanding the different types of geosynthetics, their functions, and applications, the present study highlights the comparison between geosynthetic clay liners (GCL) and compacted clay liners (CCL). There are many practical situations where a low-permeability clay or geomembranes alone are enough to prevent environmental contamination [4], although, in many instances, it is necessary to mix them, with GCL being the most appropriate [159]. They can be used for basal or cover liners in landfilling and dams as a more effective way to prevent leachate percolation and the draining of pollutants, due to their low k, and that they are more reliable than CCL. However, GCL has low shear strength and is highly compressible; in addition, the thickness of GCL generates important issues such as punctures, tears, and bursting [160]. Their k is also affected by many aspects during service, defaulting to maintain design parameters. The main factors are overlapping width, overburden-confining stress, and hydraulic head [65]. Reference [161] tested different configurations, and concluded that to control the decrease in flow through GCL with time, some techniques can be performed, such as a supplemental bentonite powder layer, a control hydraulic head and overburden-confining stress.

GCL hydration has an important role in the hydraulic conductivity, decreasing the k when performed with water before leachate permeation [52]. GCL needs to be well-hydrated following the relevant standards to achieve a low permeability, occurring by three principal sources, first from the adjacent ground, second from the liquid to be contained, such as water in wastewaters ponds or leachate in landfills, and third, and rarely, from accidents, such as accumulated rainfall in the drainage layer [65]. Reference [116] dissected the importance of hydration in the ability of GCL to contain hydrocarbons and gases, the effect of cation exchange from the adjacent soil, the effect of leachate interaction, shrinkage, the erosion of exposed liners, and the importance of the self-healing capacity of a GCL.

Reference [162] experimented on the effects of the moisture suction response of GCL with field exposure effects and changing the hydration fluid, the GCL thickness and layers, using a lightweight woven geotextile and medium-weight non-woven cover geotextile, in addition to a GCL with a woven geotextile and non-woven-cover textured 0.5 mm HDPE. The results showed differences in the moisture suction due to the hydration fluid—DW, tap water, or $CaCl_2$—and exposure conditions, but the GCL type has little effect on that relationship. Also, pre-hydration by permeation with DW resulted in k around 10^{-11} m/s, and reference [107] tested six types of GCLs permeated with coal combustion leachates having the highest k directly with leachate, and they concluded that polymeric composites could lower the hydraulic conductivity.

Additionally, Ref. [2] explicated the advantages and disadvantages of GCL due to its historic usage, physical, chemical, economical, and practical applications in Table 5.

Table 5. Advantages and disadvantages of GCL.

GCL Advantages	GCL Disadvantages
Fast installation	Low shear strength
Easy installation and repairing	High punctured probability
Low cost	Installations' loss of bentonite
Low thickness	Gas leakage when low moisture
Low k	Interface strength issues
Settlement maintenance	Lower leachate attenuation
Self-healing	Residual shear strength loss
Not dependent on the local availability	Higher long-term flux within load
Effective gas barrier	

According to [52], GCL expected service life to be very long, since there is no significant loss of bentonite during placement and there is no lateral disturbing of bentonite within hydration, maintaining bentonite distribution. Water percolation through such structures and impact factors can be measured within many equipment and methodologies, such as a modified thermo-triaxial [163] and swelling and diffusion equipment [164] for laboratorial versus industrial GCL comparison. Reference [165] made an analysis comparing the effectiveness of GCL and CCL, showing equivalency demonstrations to use both composite liners, evaluating leachate flow, the permeability soil layer, and developing an analytical method for design engineers. They concluded that a liner system with GCL is equivalent to a conventional CCL.

7. Alternative Liners

Clays have low k when well-compacted, and are therefore the natural candidate materials for barriers. However, they have been overexploited, and/or are not naturally available inside reasonable distances from the earthworks. Furthermore, soils are natural resources that should be protected. Alternative clay liners have been investigated to promote the utilization of local soils, enhancing them with additives when necessary. As mentioned before, bentonite is perhaps the most used additive for clay liners, mixed with local soils or inside GCLs. The present trend is to investigate mixtures of soils with waste, also providing a better destination for various types of residues.

Some examples of investigations about soil substitution by industrial by-products include lime mud and gypsum [166], phosphogypsum [167], furnace slags [168], mining waste [169], water treatment sludge [170–172], bagasse ash [129], wood ash [173], biosolids [174], biomass ashes [175,176], and waste fibers [177]. A review of industrial solid waste used in barriers is presented by [27].

Unfortunately, much of this research has not yet come into practice. Conventional CCLs, GM, and GCLs are still the general constituents of bottom liners. Environmental regulations governing liner materials, testing procedures, and performance standards vary across jurisdictions, and it is crucial to align research findings with these frameworks. A comparative analysis of global regulatory standards, such as the European Waste Framework Directive, the U.S. Environmental Protection Agency (EPA) landfill regulations, and international ISO guidelines, can provide valuable insights into best practices and compliance strategies.

Moreover, policy-driven research should explore how alternative liner materials can meet existing regulatory requirements or drive the development of updated standards. Engaging with policymakers, industry stakeholders, and environmental agencies will facilitate the integration of sustainable liners. Future research should also examine economic incentives and funding mechanisms that support the adoption of eco-friendly liner solutions, ensuring their feasibility and long-term success in waste containment infrastructure.

8. Discussion

The authors have developed Tables 6 and 7, summarizing future trends for investigation of liners structures and materials, respectively. These barriers help prevent hazardous substances in the soil or water, mitigating environmental risks for the sustainable use of natural resources [32]. Effective geotechnical and hydraulic barriers prevent soil erosion and landslides, and provide better management of water resources; in addition, landfilling can redevelop brownfield sites, promote sustainable land use and urban planning, and contribute to the overall well-being of society [178].

Due to a future shortage of natural resources in addition to the growing generation of waste, the following is the main finding emerges: to reduce the amount of waste generated and to develop strategies to prevent the contamination of soil and water by waste [65]. This paper indicates that this can be achieved by combining waste management and structural design optimization. Designs should involve the use of new and feasible materials, the enhancement of properties, laboratory data analysis, and modeling different solicitation scenarios.

From the authors' perspectives, environmental protection aligns with both the global context and the specific challenges and opportunities within the country. Specifically, Portugal's main points to consider are coastal protection as a result of long and vulnerable coastal ecosystems, and better water management of fluvial and pluvial waters due to periodic droughts providing support for agricultural supply, a very important Portuguese economical sector. Agriculture is also impacted by the sustainable land use abovementioned, preserving fertile soil, monitoring land degradation, and conservating biodiversity. As Portugal attracts a significant number of tourists, and its cultural heritage sites are important for the economy, this will encourage investments in renewable energy infrastructures, urban planning and redeveloped of degraded areas. This perspective aligns with both national priorities and broader efforts to achieve environmental sustainability. Global action and personal attitudes toward environmental protection are multifaceted and often involve education for environmental consciousness and awareness campaigns and initiatives, which can help people understand how their actions impact the environment and their role to protect ecosystems, lead to governments supporting companies, and also support industries that prioritize ecosystem protection, also promoting regulations for responsible use of resources. This highlights the importance of joining individuals, researchers, practitioners, and politics to influence the processes.

While this paper provides a review of liner materials, we acknowledge the need for further research into sustainable and innovative materials [179]. Future investigations should focus on emerging alternatives such as bio-based geomaterials, recycled industrial by-products, and composite liners that integrate various waste streams to enhance performance. Microbial-induced [180] or nature-based solutions [181] may also provide sustainable solutions with self-healing properties, reducing maintenance costs and extending service life. Additionally, novel structures, such as multi-layered hybrid liners combining natural and synthetic materials, should be explored for their potential to optimize hydraulic conductivity, mechanical stability, and chemical resistance in landfill and water containment applications [109]. To address this research gap, future studies should include laboratory testing, numerical modeling, and the field-scale validation of alternative materials and structures. By expanding the scope of materials and structural innovations, geoenvironmental engineering can move towards an environmentally friendly liner system.

While the Discussion approached the impact of liner structures on air quality, soil contamination, and water pollution, a more comprehensive evaluation of long-term ecosystem health and biodiversity effects is needed [113]. Liners play a crucial role in preventing the migration of contaminants; however, their influence on microbial activity, soil fertility, and local biodiversity remains underexplored. The potential leaching of chemical compounds from liners, including heavy metals and microplastics from geosynthetics, must be thoroughly assessed through long-term monitoring studies. Nonetheless, future research should incorporate ecological impact assessments that evaluate changes in vegetation cover, groundwater-dependent ecosystems, and aquatic biodiversity near containment facilities. Additionally, life cycle assessments (LCA) of liner materials should be conducted by integrating these factors into liner design and implementation [182]. To strengthen this aspect, we highlight other authors who have incorporated detailed case studies that evaluate liner performance in operational waste containment sites, tailings dams, and wastewater treatment facilities. Several aspects like site-specific challenges, material selection criteria, and long-term monitoring data to assess structural integrity, permeability behavior, and environmental compatibility, improve the literature on the topic. Moreover, pilot-scale projects and full-scale field applications should be explored to validate the findings of laboratory experiments.

However, the complexity of liner behavior is well-known, requiring advanced methodologies to accurately assess their mechanical, hydraulic, and chemical performance over time. Future research should incorporate high-resolution geophysical monitoring tools, such as electrical resistivity tomography and ground-penetrating radars, to detect structural changes and potential leakage in liners [183]. Additionally, integrating numerical modeling approaches and computational fluid dynamics can improve predictions of liner performance under varying environmental conditions. Advanced statistical models and machine learning techniques should be employed to analyze large datasets and identify trends in material behavior [184].

The main contribution of this state-of-the-art review is related to providing a comprehensive overview of the literature, helping students, researchers, and practitioners, along with the tables and figures designed by the authors. Figure 1 analyses bibliometric aspects to identify trending keywords and subjects while reviewing the theme, like yearly distribution and the main countries where it is studied. Tables 1, 2 and 5 identify the toxicity limits for several governmental directives, the main parameters to classify a material as liner-usable, and the usually used clays properties. They represent the available prospects for researching alternative materials. Then, evaluating the properties of a candidate as s liner, Figure 5 shows the cycle that should be assessed when dealing with “forever chemicals” contaminants, going over identification, quantification, and remediation techniques, substitute analysis, and directives development for mitigating environmental pollution. And, regarding the practical application of new materials, Tables 6 and 7 investigate gaps and topics that should be linked with Figure 7 liner design, according to the on-going regulation of construction. The integration of all that knowledge, synthesizing information from the main references on geotechnical, hydraulic, and environmental aspects, should be used as a guideline.

Table 6. Investigation trends for liner infrastructures.

Main Investigation	Investigation Area	References
Waste management	Landfilling techniques	[185–189]
	Waste valorization	[190]
Monitoring	Storage instrumentation	[8,9,107]
	Containment instrumentation	[191]
Structural	Storage design	[3,51–53,55–58,192,193]
	Containment design	[194,195]
Waste treatment	Bioremediation techniques	[196–198]

Table 7. Investigation trends for liner materials.

Main Investigation	Investigation Area	References
New materials	GCL with recycled materials	[141,142]
	Geocomposites	[149,150]
	Bentonite–soil mixtures	[122,123,125,166,199–204]
	Bentonite design	[121,205–207]
	Soil–waste mixtures	[27,28,169,172,175,208–212]
Properties enhancement	Geomembrane durability	[132–134,138]
	Geomembrane reinforcement	[135]
	Geomembrane–polymer additive	[140,141]
	Bituminous	[149,150]
	CCL-biogeopolymer	[110,114,213–215]
	CCL chemical enhanced	[112,113,115,116,121,216–218]
	CCL leaching compatibility	[108]
Modeling behavior	GCL layer design	[107,162,219]
	GCL long-term	[220–223]
	GCL compatibility	[107,116,224]
	Geomembrane long-term	[139]
	Geomembrane stress scenario	[153,154]
	CCL durability	[125,225,226]
	CCL compaction	[120,184,201]
	CCL thermal effect	[219,227–229]
	Long-term design	[111,120,125,225,230]
Workability	Testing methodology	[163,164]
	Interface interaction	[149,155,231]
	Construction technique	[161,232]

Regarding scientific innovative pathways and strategies, the review mainly overlooked green technologies and sustainable infrastructure, which embrace circular economy principles using nature-based, biotechnology, and bioengineering solutions. Indeed, smart technologies, such as AI and the Internet of Things (IoT), attached to environmental objectives are the future for sustainability investigations. Developing and implementing green technologies, such as renewable energy systems, sustainable building materials, and eco-friendly infrastructure, and innovation in construction and engineering practices can contribute to environmentally friendly solutions.

9. Conclusions

This study reviewed the properties, parameters, and applicability of geomaterials used as liners for environmental protection, with a focus on their geotechnical and hydraulic behavior. The analysis highlighted key materials such as CCL, GCL, and alternative industrial by-products, demonstrating that while traditional materials are widely used, innovative materials, such as waste-based liners, can enhance environmental sustainability while maintaining the required performance standards. The research also examined design optimization, structural integrity, and contamination control, reinforcing the importance of the proper selection, testing, and implementation of geomaterials for waste storage and containment applications.

Despite these advances, further research is necessary to improve the facts that:

- CCL research is increasingly focused on modifying CCL with biogeopolymers to improve durability and hydraulic performance; exploring chemical additives to reduce permeability and enhance compatibility with leachates; analyzing the impact of different waste leachates on CCL integrity, ensuring long-term stability; and assessing the influence of compaction parameters and temperature variations.
- GCL investigations are integrating recycled materials to improve sustainability and reduce costs, focusing on long-term performance, especially regarding chemical resistance and mechanical stability; and studies are refining the design of GCL layers to enhance their hydraulic properties under various environmental conditions.
- Geomembranes studies are exploring long-term chemical exposure, temperature fluctuations, and mechanical stress; the feasibility of using recycled polymers while maintaining barrier efficiency; and assessing the interaction with different liner materials, optimizing performance for landfill and wastewater applications.
- Industrial by-products valorization focuses on incorporating industrial waste materials such as slags, ashes, and sludges to develop cost-effective, sustainable liners; determining the most effective waste–soil mix ratios to achieve low permeability and high stability; overlooking microbial activity and chemical reactions within this interaction.
- Instrumentation and monitoring advanced sensor technologies are being explored in real-time monitoring systems, including IoT-based sensors, which can improve the detection of leaks and performance changes in liners; the use of AI-driven predictive modeling is emerging as a tool to optimize liner design and performance assessment for numerical modeling.

Nonetheless, the waste crisis is an ongoing phenomenon which is affecting economic and environmental aspects of society, waste management techniques, and regulatory frameworks, and sustainable measures are being investigated to mitigate soil and water contamination. Regarding those structures, the most studied subjects are design optimization, waste management directives, and the most important, monitoring and instrumentation of the construction itself, attaching numerical modeling to long-term, durability, and extreme scenarios simulation.

Thus, there are other types of materials, like by-products mixtures, which enhance the performance of liners in environmental sealing. Geotechnical feasible residues and bio- and nature-based materials, with straight directives for valorization, emerge as innovative solutions. Following this, economic and geoenvironmental sustainable actions can be achieved and improved.

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