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TITLE

Geosynthetic applications in environmental sectors.

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ABSTRACT

Geosynthetics are now essential in environmental engineering, but their effectiveness, advantages and rules for use vary from one region to another. This thesis uses decades of case studies, investigations and reviews from the United States, the United Kingdom, Quebec, Iran and Italy to study the relationship between design, construction quality assurance and legislation. When geomembranes, bentonite seals and drainage layers are used together and proper inspections, certified installation and testing are applied, the systems remain reliable after minor damage; this results in almost no seepage, stable slopes and a significant drop in remediation costs, but if these measures are not taken, the field performance is not consistent and downstream expenses rise. While high temperatures and strong chemicals can speed up ageing and decrease the service life of geosynthetics, studies show that using geosynthetics results in less excavation, quicker construction and less greenhouse gas, making them better for the environment and more economical than clay or concrete in containment, transport and water management. If biodegradable erosion blankets, recycled-polymer geogrids and sensor-enabled liners are proven to last and are supported by proper procurement, they could help make these sustainability gains even stronger. All in all, the research reveals that geosynthetics are used to their full advantage when composite design, strict quality control and proper regulation are applied, and it provides useful advice to help engineers, regulators and asset owners build strong and environmentally friendly infrastructure.

Keywords: Geosynthetics, Regulatory frameworks, slope stability, Landfill containment, Drainage geonet

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LIST OF ABBREVIATION

Abbreviation	Full name
RCRA	Resource Conservation and Recovery Act
CWA	Clean Water Act
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
EPA	Environmental Protection Agency
HDPE	High-Density Polyethylene
SUDS	Sustainable Urban Drainage Systems
GCLs	geosynthetic clay liners
RCRA	Resource Conservation and Recovery Act
BAT	Best Available Technique
ICMM	International Council on Mining
CQA	Construction Quality Assurance
FHWA	Federal Highway Administration
AASHTO	American Association of State Highway and Transportation Officials
LFE	Landfill Environmental
HSE	Health, Safety, and Environment
MTQ	Manufacturing Test Quality
MSW	Municipal Solid Waste

EC	Electrical Conductivity
ISO	International Organization for Standardization
TRMs	Turf Reinforcement Mats
GEMS	Geosynthetic Erosion Control Materials
FEMA	Federal Emergency Management Agency
ETCs	Electronic Toll Collection systems
GRS	Geosynthetic Reinforced Soil

CHAPTER 1: INTRODUCTION

1.1 Overview

Global natural ecosystems experience unprecedented stress from three main causes which include urbanization and climate change and resource depletion of non-renewable resources. The emerging environmental problems have shifted the focus toward developing innovative sustainable engineering solutions which combine cost effectiveness with environmental responsibility. Engineers dedicate research efforts to environmental footprint reduction technologies alongside overall system optimization because of these developments. Geosynthetics have proven vital for modern infrastructure projects by delivering resilient versatile solutions to the field.

Synthetic polymer-based geosynthetics represent essential products which have found wide application in geotechnical and environmental engineering. Engineers apply a range of geosynthetic materials, including geotextiles, geomembranes, geogrids, and geocells, to perform specialized functions like filtration and stabilization. Using geosynthetics as replacement materials offers several benefits, including minimizing environmental impact and improving performance in engineering projects. Geosynthetics offer substitute solutions for conventional construction techniques in a wide range, such as road development and water resource management. (Abedi et al. 2023)

Also, The use of geosynthetics provides effective protection for areas vulnerable to severe soil erosion caused by heavy rainfall, flooding, or steep slopes. When applied to slope surfaces, geocells combined with geotextiles improve soil shear strength, reduce surface runoff, and promote vegetation growth. Geosynthetic techniques work to stop erosion and sediment deposition in nearby water bodies at the same time that they build ecological stability for plant growth. The combination of geosynthetic solutions with Italian soil showed considerable success to protect slopes against severe weather by decreasing soil erosion while boosting stability(Limoli et al. 2019).

The field of waste management experienced a game-changing transformation because geosynthetic materials solved fundamental problems in traditional liner systems within landfill construction. When landfills operated during their early years the leachate flowed into both surrounding soils and underground groundwater systems. Modern landfills implement advanced liner solutions which unite geomembranes with geosynthetic clay liners (GCLs) and drainage geocompound materials and geonets to block toxic fluids from escaping. The coordinated system design prevents the release of dangerous materials into the surrounding water sources which maintains both the local water supply and wider environmental security. Studies conducted in U.S. fields show these systems built following RCRA protocols are highly effective at preventing pollution of the environment (D. Wang et al. 2023).

Geosynthetics demonstrate significant potential growth in water conservation while handling wastewater because of their expanding applications beyond erosion control and landfill engineering practices. The technology serves to encapsulate irrigation ponds and reservoirs and wastewater treatment facilities to avoid leakage and safeguard water sources against pollution. Infrastructure projects benefit from these applications through water resource preservation that leads to improved sustainability performance. Geosynthetic products will experience substantial market growth because various nations are implementing sustainable development strategies. Geosynthetics serve as essential technology because they present multiple functions at affordable costs while being environmentally suitable(Poberezhnyi, Hangen, and Lenze 2023).

1.2 Objective of the study

The study presents a comparison between Iran, Canada, Italy, United States, and United Kingdom. By evaluating geosynthetics approaches, local environmental conditions, and legal constraints in various locations, the research aims to determine the cost-effectiveness and sustainability benefits of utilizing geosynthetics. This multi-regional approach highlights the opportunities of geosynthetic technology to promote robust and sustainable waste management systems all around as well as brings out worldwide best practices.

1.3 Organization of the Thesis

This thesis is organized into five chapters, beginning with Chapter 1, which introduces the research problem, objectives, and the role of geosynthetics in landfill engineering. Chapter 2 reviews the regulatory frameworks, detailing technical regulations and standards across various regions, while Chapter 3 presents a comprehensive literature review on geosynthetic applications and their performance. Chapter 4 outlines the methodology employed for data collection and analysis, and presents the results of the comparative study. Finally, Chapter 5 discusses these findings, draws conclusions, and offers recommendations for future research.

CHAPTER 2. REVIEWS THE REGULATORY FRAMEWORKS

2.1 Overview:

In this chapter, the significance of geosynthetics in environmental engineering is thoroughly examined. The focus of the conversation is on the regulatory frameworks that oversee their use and their application in waste management systems, with a particular emphasis on landfill design. The analysis emphasizes the different degrees of regulatory enforcement and technological advancements by comparing practices across regions, including the United States, the United Kingdom, Quebec (Canada), Iran, and Italy.

2.2 United State U.S

The U.S. employs geosynthetics across diverse environmental applications under regulatory frameworks such as the Clean Water Act (CWA) and Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Two main geosynthetic materials known as geotextiles and geocells provide essential functions for protecting coastal areas from erosion and for maintaining riverbank stability and cleaning polluted soil. The EPA leads standardization efforts for geosynthetic application through initiatives such as Brownfield Redevelopment programs that specify geosynthetic-retained walls together with geomembrane barriers to contain contaminants throughout property redevelopment projects. Coming under the Superfund Remediation regulations of CERCLA the EPA demands composite liners involving HDPE geomembranes and geosynthetic clay liners as hazardous waste barrier systems.

The agency promotes project use of permeable geocomposites in stormwater management while using its National Stormwater Calculator to fulfill National Pollutant Discharge Elimination System (NPDES) requirements for urban runoff reduction.(von Maubeuge, Shahkolahi, and Shamrock 2023; Reinhart 1993; Y. Wang, Levis, and Barlaz 2021)

2.3 United Kingdom, UK

Geosynthetics receive integration in environmental protection through two regulatory frameworks including the Environmental Permitting Regulations (2016) and EU Water Framework Directive. Geotextile tubes and geobags together with geocomposite drainage layers serve multiple applications in flood defense systems as well as green infrastructure for sustainable urban drainage systems (SUDS). Engineers use geomembranes as a restoration method in aquatic habitats because they isolate polluted sediments in lakes and rivers. The Environment Agency requires geosynthetic materials to demonstrate strong durability against saltwater damage when used in marine applications.(Pratt and Dixon 2003; Waite 2017)

2.4 Quebec, Canada

Under laws established by Quebec's Mining Act and Environmental Quality Act the government regulates all uses of geosynthetics for mining operations as well as ecosystem restoration practices. The regulations require geomembranes and geosynthetic clay liners (GCLs) for tailings pond liners to stop acid mining runoff and geotextile tubes serve as the stabilization element for wetlands negatively affected by industrial operations. Through its policies the province uses geocells for Arctic Road building as they protect against permafrost degradation. The geosynthetic requirements of Quebec surpass the national regulations because manufacturers need to receive independent verification for their products in environmental protection zones. (Malmir et al., 2023)

2.5 Iran

The National Environmental Policy of Iran supports the use of geosynthetics to control desertification and develop arid-region agricultural practices. Geotextile serve to stabilize sand dunes across the Dasht-e Kavir and geocomposite irrigation systems function to boost water efficiency in farmlands. The limited nature of enforcement does not prevent National Adaptation Plan projects from utilizing geogrid-reinforced terraces to fight against mountainous soil erosion across locations. The utilization of geotextiles faces two main obstacles consisting of material spending and dependency on imported polymers but scientists in the region investigate the possibility of developing geotextiles through natural fiber sources.(Alielahi, Derakhshan, and Kalhor 2024; Pasalari et al. 2019; Yazdani et al. 2013)

2.6 Italy

Italian regulations are intricately linked to European Union directives and are enshrined in national legislation, including D.Lgs. 152/2006. In order to prevent effluent from contaminating groundwater, the EU Landfill Directive requires Italian landfills to employ composite enclosures. A singular composite liner, such as a geosynthetic clay liner (GCL) or an HDPE geomembrane over the clay, is typically necessary for non-hazardous waste. A double-liner system is necessary for hazardous waste locations(Limoli et al. 2019). Geosynthetic liner testing and electrical leak investigations are mandatory in regions such as Lombardy, where more stringent standards are enforced. Geosynthetic materials are influenced by Italy's approach to mining detritus and past environmental calamities, and they strictly adhere to EU Directive 2006/21/EC. Recent research indicates that Italian engineers frequently implement geogrids and geotextiles for slope stabilization, despite the absence of a specific legal mandate for the use of geosynthetics in landslide mitigation.(Agovino, Ferrara, and Garofalo 2016; Agovino, Garofalo, and Mariani 2016; Limoli et al. 2019)

2.7 Comparison

The table below summarizes key regulatory requirements and technological applications of geosynthetics in each region and emphasized on technical regulations for landslides (various types, domestics, industrial mining waste in these countries

Table 1: Regulations and Geosynthetic Applications by Country

Country	Landfill Regulations (liners, etc.)	Mining Waste Regulations (tailings)	Landslide & Slope Applications
USA	RCRA (Resource Conservation and Recovery Act)Subtitle D (EPA) – Requires composite liner (≥30 mil geomembrane + 0.6 m clay) for MSW landfills . Subtitle C (hazardous) – Double liner with leak detection. 2015 EPA rule extends composite liners to coal ash impoundments . States enforce CQA.	No specific federal liner mandate for mine tailings (Bevill exemption), but coal ash ponds now regulated . Many mines use geomembranes as BAT best available technique voluntarily. Dam safety governed by state/federal guidance; ICMM International Council on Mining and Metals global standard influencing practice.	Geosynthetics widely used in slope stabilization (geogrid walls, reinforced soil slopes). FHWA/AASHTO guidelines include geosynthetics. Not mandated by law, but proven in projects like a 110’ (33 m) geogrid buttress in California
UK	EU Landfill Directive 1999/31/EC (applied until 2020) – Required low-permeability base liner for all landfills, usually HDPE (+High-Density Polyethylene clay landfill-site.com . National regs (2002) implemented this. Environment Agency guidance (LFE series) specifies use of GCLs, geomembranes, CQA protocols gov.uk . Post-Brexit, EU standards retained in UK law.	EU Mining Waste Directive 2006/21/EC – Requires permits & *BAT* for tailings. UK regulators may require liners or seepage control based on risk. Emphasis on water quality and dam stability (HSE)– (**Health, Safety, and Environment)**. Generally, high-risk tailings facilities include geomembrane liners or covers; lower-risk may rely on natural attenuation.	Geosynthetics in standard practice for slopes: e.g. geogrid-reinforced rail embankments, geotextile drainage for coastal cliffs. No direct mandate, but design standards (BS 8006) cover reinforced soil. Many municipal projects use geocells and mats for erosion control.

Country	Landfill Regulations (liners, etc.)	Mining Waste Regulations (tailings)	Landslide & Slope Applications
Iran	Waste Management Law (2004) – General duty to prevent pollution, but **no specific liner requirements**. Many landfills are unlined or use only clay. A few recent landfills (Tehran, Mashhad) incorporated geomembranes by following international standards, but there is **no dedicated Iranian standard** forcing their use.	No specialized mining waste regulation; governed under general environmental law. Tailings storage largely unregulated apart from needing an environmental permit. Most tailings ponds in Iran are unlined; a few newer projects with foreign partners have begun using geomembranes or geosynthetic covers for acid mine drainage control.	Use of geosynthetics in landslide mitigation is emerging. Iran faces quake-triggered landslides; studies have tested geosynthetic liners to improve seismic stability of slopes and landfills ceej.aut.ac.ir . Implementation on the ground is limited but growing, as engineers see successful examples abroad and in research.
Canada	Quebec Q-2, r.19 Landfill Regulation – Requires engineered liners for all new landfills. In permeable soil areas, a **double liner** (clay + 2 HDPE membranes) and dual leachate collection are mandatory. Even in good natural clay sites, a composite liner is standard. High level of enforcement by provincial environment ministry.	Federal guidelines (Metal Mining Effluent Regs) and provincial rules ensure tailings management plans. No blanket requirement for geomembrane liners in tailings, but **recent practice** post-2014 is to consider liners to prevent acid drainage. Oil sands tailings (outside Quebec) use geosynthetics in covers. In Quebec, any mine waste facility near sensitive aquifers likely requires a liner or barrier by permit conditions	Similar to rest of Canada: geosynthetics used for slope stabilization in infrastructure. E.g., geotextile filters and geogrids in highway embankments over soft clay or permafrost. Not mandated, but provincial guides (MTQ) (Ministère des Transports) include geosynthetic options for embankment and retaining wall design.

Country	Landfill Regulations (liners, etc.)	Mining Waste Regulations (tailings)	Landslide & Slope Applications
Italy	Italian Environmental Code (D.Lgs 152/2006) – Aligns with EU Landfill Directive: composite liners (HDPE + clay/GCL) required for MSW; hazardous landfills need double barriers. Regional rules add strict quality control (e.g. Lombardy requires liner integrity tests). All landfills must protect groundwater and have leachate systems	Directive 2006/21/EC on mining waste adopted in Italy – Tailings facilities need a safety permit. Liners not explicitly mandated for all, but authorities can require geomembranes for toxic tailings. Focus on preventing disasters (post-Stava). Some Italian mines lined their tailings ponds as a preventive measure (case-by-case).	Geogrid and geotextile solutions heavily used in Italy's landslide mitigation (one of EU's leaders). Geosynthetic-reinforced slopes up to 60 m high have been built to stabilize landslides. Government funds slope repairs often include geosynthetic drainage and reinforcement, based on engineering design.

As the table shows, the regulatory actions taken for landfill management vary greatly among the different areas. The RCRA system requires composite liners for both municipal solid waste (MSW) and hazardous waste dumps in the United States. These liners have to satisfy specific requirements including a minimum of 30 millimeters of high-density polyethylene (HDPE) geomembrane and a 0.6-millimeter clay thickness. Moreover, the RCRA framework covers coal ash impoundments in line with present Environmental Protection Agency (EPA) guidelines. Conversely, the United Kingdom follows the European Union Landfill Directive, which calls for low-permeability base liners constructed usually out of low-density polyethylene (HDPE) mixed with clay. National guidelines stressing geosynthetic clay liners (GCLs) and strict Construction Quality Assurance (CQA) requirements support this direction. Italy uses twin barriers for hazardous wastes and composite liners for municipal solid trash in compliance with the EU. These are enhanced by regional quality standards including required liner integrity testing in Lombardy. Some of the strictest rules, which call for designed, double-liner systems in permeable regions, come from Quebec, a province of Canada. Conversely, the Iranian Waste Management Law just provides a general guidance to prevent contamination. Many Iranian landfills so either depend exclusively on clay or are unlined. But modern constructions are beginning to include geomembranes in line with international standards.

The legislative environment shows a similar degree of variation in terms of the prevention of mining waste and landslides. The United States of America does not mandate mine tailings liners based on restrictions including the Bevill exemption. Still, the most efficient method presently accessible for mining operations and regulated coal ash ponds is the voluntary use of geomembranes. The Mining Waste Directive of the European Union mandates the adoption of risk-based management approaches and permits for high-risk sites; the United Kingdom is a member of this body. These techniques can be needed for seepage control devices or liners. By comparison, Iran's policies on mining waste are still under development. Except for certain more recent projects including the use of geomembranes or geosynthetic covers to help to manage acid mine drainage, tailings facilities are frequently not lined. Quebec adopts federal and provincial guidelines that gradually support liner applications, particularly in close proximity to sensitive aquifers, notably. Conventional engineering practice uses geosynthetics extensively in the United Kingdom and the United States of America. This is so even though geosynthetics are not legally required in any place for landslide and slope stabilization. Leading in this area with advanced uses including geosynthetic-reinforced slopes up to sixty meters high is Italy. These programs show substantial governmental support as well as high technical ability. Conversely, Iran is only beginning to apply geosynthetic techniques to help with slope stabilization.

2.8 Summary

Geosynthetics, which are engineered plastic materials, are utilized in numerous environmental applications and have become critical components of contemporary environmental engineering. Their diverse applications, which range from stabilizing slopes and managing water to enclosing landfills and containing mine refuse, have revolutionized waste management and facilitated the preservation of natural resources. As the severity of environmental issues such as contaminated groundwater, waste management, and the risk of landslides increases, geosynthetics become increasingly important in mitigating their severity. (Milford 2018)

The regulations governing the use of geosynthetics are highly variable across the globe. This is because each region has its own unique technological advancements and environmental concerns. The Environmental Protection Agency (EPA) in the United States is subject to stringent regulations established by the Resource Conservation and Recovery Act (RCRA). For instance, composite covers are required for hazardous and non-hazardous waste sites. In contrast, the United Kingdom and Italy adhere to European Union guidelines emphasizing performance-based standards. Local laws in Quebec, Canada, frequently implement even more stringent regulations. Simultaneously, Iran's legislation gradually incorporates foreign best practices, even though they have not always been applied rigorously. ((Touzé 2022; Waite 2017)This summary examines geosynthetics's technical, legal, and practical aspects in five critical regions: the United States, the United Kingdom, Quebec, Iran, and Italy. It accomplishes this by comparing the construction of landfills, managing mine refuse, and preventing landslides. Many studies emphasize the interplay between government regulations and emerging technologies. This demonstrates the significance of conducting a comprehensive investigation and adhering to the regulations to enhance the world's sustainability and safety. Establishing rigorous standards by environmental protection agencies such as the U.S. EPA and organizations that adhere to EU regulations has resulted in advancements in applying geosynthetics globally. ((Rowe and Fan 2024a))

CHAPTER 3: LITERATURE REVIEW

3.1 overview:

Environmental engineering utilizes a wide spectrum of geosynthetics including geomembranes and geotextiles and geogrids as well as geocomposites and geonets to resolve environmental issues. These sustainable and economical solutions from geosynthetics help waste management practices together with erosion protection and pollution cleanups of land as well as serving transportation infrastructure requirements. This complete scientific literature review presents both international trends using case studies from Iran and the U.S. along with regional differences from Britain and Canada and technical innovations from multiple countries which includes Iran and the U.S. and U.K. and Canada and Italy. It also embraces a structured research design for achieving rigorous and replicable results.

Engineered geosynthetic solutions serve the purpose of solving vital environmental problems in waste storage and erosion reduction and protecting groundwater resources. studies including (Müller and Saathoff 2015) show that these materials extend structural endurance by performing well as drainage systems and prevention barriers against contamination. The U.S. Environmental Protection Agency recognizes geosynthetic applications in landfills because they enable environmentally friendly waste management and reduce the ecological impact (Henken-Mellies, Zanzinger, and Gartung 2022). Researchers continue to debate about the extended environmental effects that include microplastic waste and recycling difficulties despite proving their worth. The protection of ecosystems and advancement of sustainable practices depend heavily on biodegradable alternatives research by (Palmeira, Araújo, and Santos 2021a)and findings from (Chatrabhuj and Meshram 2024).

3.2 Types of Geosynthetics and Their Functions:

The family of geosynthetic products includes geotextiles and geogrids and geomembranes and more according to the definitions provided by mdpi.com. Permeable textile fabrics help accomplish separation tasks alongside filtration and drainage functions and stop soil mixing to protect fluid flow with their particle retention ability. Geogrids represent stiff polymer meshes which primarily serve for reinforcement functions by joining with soil or aggregate matter to spread loads and maintain stability (Dąbrowska et al. 2023). Geomembranes represent impermeable liners mainly constructed from HDPE which block liquids and gases to ensure proper waste containment and groundwater protection (mdpi.com). By uniting bentonite clay material with geotextiles or geomembranes the geosynthetic clay liner (GCL) system produces a hydrological barrier that accomplishes self-sealing functions during contact with moisture. Les tres de Geonet et les Geocomposites describe three-dimensional synthetic structures and composite combinations of geotextile and geonet which serve to drain horizontally and find applications in leak detection layers and landfill drainage systems. Geocells function as three-dimensional confinement systems with honeycomb-shaped characteristics that stabilize slopes while supporting weak soil loads. Geosynthetic erosion control mats together with geofoam and geopipes qualify as geosynthetic products when applied in earthworks operations. Each type of geosynthetic material performs at least one fundamental function from among separation, reinforcement, filtration, drainage, barrier and protection. Nonwoven geotextiles placed under riprap function both as filtration components that separate particles from water streams and as erosion control features that provide water passage but prevent soil damage (Dąbrowska et al. 2023). Simultaneously geomembranes in landfill bases act as pure leachate prevention barriers. Multiple geosynthetic materials work along with one another in layered installation systems where landfills typically contain a geomembrane at the top of a GCL while a geotextile acts as a protective element and a geonet facilitates leachate drainage. When installed together these complex systems function as an interlocked “composite lining” which captures the best features of all participating materials. The combination of geotextiles with geomembranes and drainage geonets provides tunnel infrastructure with engineering functions for drainage and cushioning behind the waterproofing layer(Daniele Cazzuffi, Gioffrè, and Luciani 2023). The environmental functions including containment liners and filters form among a list of common geosynthetic types as explained in Table2 which demonstrates these materials' broad design potential.

Table 2: Common Geosynthetics and there with brief descriptions

Geosynthetic Type	Primary Function(s)	Typical / Notable Uses	Key Technical Properties	Brief Description
Geotextile (woven & non-woven)	Filtration, separation, drainage	• Filtration layers in drains• Separation between dissimilar soils• Sub-drainage behind walls & under roads• Erosion-control wraps & coastal mats• Cushion/protection over geomembranes	• High permeability while retaining soil (AOS)• Tensile strength & elongation at break• Puncture & abrasion resistance	Permeable fabric that lets water pass while holding soil particles back; invaluable for keeping layers apart and relieving pore-water pressures.
Geomembrane (HDPE, PVC, etc.)	Barrier / containment	• Base and cap liners for landfills & mining tailings• Waste-water, slurry & process ponds• Canal, reservoir and secondary-containment liners• Slurry walls & cutoff diaphragms	• Ultra-low hydraulic conductivity (~10^{-13} m/s)• Chemical & UV resistance (HDPE excels)• High tensile & tear strength• PVC offers superior flexibility	Impermeable polymer sheet that blocks liquid or gas migration and provides long-term containment (30–100 yr service life with proper cover).
Geogrid (uniaxial / biaxial)	Reinforcement & load distribution	• Subgrade stabilisation in paved/unpaved roads• Rail embankments & working platforms• Reinforced soil slopes and MSE walls• Load transfer in airport and port pavements	• Tensile strength 20–200 kN/m• Junction efficiency & aperture size (soil interlock)• Creep resistance for sustained loads• Durability against UV & chemicals	Stiff polymer grid that interlocks with aggregate or soil, taking tensile loads that soil cannot—the backbone of many reinforced-soil systems.
Geonet	Drainage (in-plane flow)	• Leachate and gas collection layers under landfill caps• Drainage behind retaining walls & tunnels• Capillary barrier / venting systems	• High in-plane flow capacity• Compressive strength to resist overburden• Thickness and long-term creep resistance	Net-like, three-dimensional core that transmits fluids laterally, often paired with a geotextile filter or a geomembrane barrier.
Geosynthetic Clay Liner (GCL)	Low-permeability composite clay barrier	• Secondary liners beneath geomembranes• Hydraulic barriers in canals, reservoirs & tailings dams• Cutoff walls and capping of contaminated sites	• Hydraulic conductivity 10^{-9}–10^{-11} m/s• Bentonite swelling & self-sealing• Internal shear strength & self-healing• Thickness 5–10 mm	Factory-bonded layer of bentonite between geotextiles or geomembranes; swells to form a durable, self-sealing barrier against liquids.

Geosynthetic Type	Primary Function(s)	Typical / Notable Uses	Key Technical Properties	Brief Description
Geocell	Confinement & soil stabilization	• Slope and channel erosion control• Base reinforcement for heavy-duty pavements• Embankment support over weak soils• Green roofs, tree-root protection, retaining facings	• Cell size/depth and strip wall thickness• Weld-joint & material tensile strength• Stiffness, elastic modulus & UV/chemical resistance	Honeycomb-like 3-D cells that confine infill, greatly increasing its bearing capacity and resistance to shear or erosion.
Geocomposite	Combined drainage, filtration &/or barrier	• Leachate and gas drainage in landfill liners/caps• Vertical/horizontal drains behind structures• Waterproofing in tunnels, bridge decks, roofs	• High in-plane flow rate (from geonet/core)• Tensile strength (from geotextile layer)• Chemical resistance & low permeability (from geomembrane layer)	Engineered multi-layer product—often geotextile + geonet or geotextile + geomembrane—tailored to deliver two or more functions simultaneously.

3.2.1 Recycled fills and circular-economy perspectives

Recent classification frameworks extend geotechnical index testing to excavation spoils and glass/ceramic granulates, allowing them to serve as drainage blankets or cover soils while cutting GHGs by up to 35 % compared with virgin aggregate haulage (Oggeri and Vinai 2020).

3.3 Design-Method for Geosynthetics

- **Geomembrane**

The primary function of impermeable polymer sheets (HDPE, LLDPE, PVC, EPDM, PP) known as geomembranes (Figure 1) is to serve as fluid barriers through design calculations based on hydraulic head and leakage assessment (Koerner 2012). The sheet thickness and puncture/tear resistance and tensile yield and ultimate strength (ASTM D6693) and ESCR and OIT and seam peel/shear are evaluated against limits that incorporate damage reduction factors and temperature and chemical exposure considerations to maintain long-term containment performance in liners, caps, and reservoirs.

Figure 1: Geomembrane

- **Geogrid**

Geogrid (Figure 2) polymeric meshes reinforce soils by mobilising tensile strength and pull-out resistance through Giroud–Han or multilayer elastic methods that utilize short-term and creep-reduced tensile strengths (ASTM D6637, D5262) with interface friction or pull-out data (ASTM D6706) to determine layer sizes and anchor lengths for pavement bases, embankments and MSE walls. For dynamic rock-fall loading, (Ronco, Oggeri, and Peila 2009) derive a semi-empirical design chart calibrated on>40 explicit FE simulations that links allowable face displacement to impact energy and reinforcement spacing, offering a practical alternative to full transient analysis.

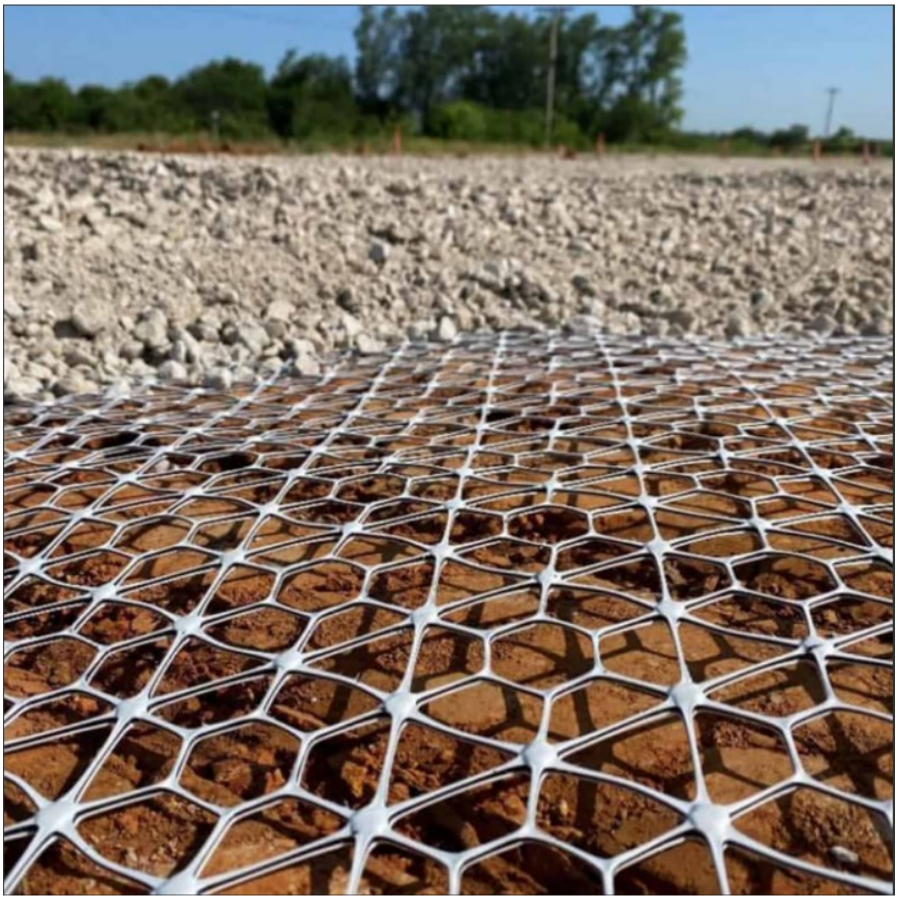

Figure 2: Geogrid

- **GCLs**

Geosynthetic Clay Liners (GCL)(Figure 3) represent composite materials filled with bentonite that serve as thin barriers with saturated conductivities between 10^{-11} and 10^{-10} m/s. Design procedures verify area density and swelling behavior and long-term permeability (ASTM D5887) and internal and interface shear strength (ASTM D6243) for Darcy flow and slope stability assessments in landfill and pond liners.

Figure 3: GCLs

- **Geocomposite**

Geocomposites (Figure 4) consist of layered products that combine drainage cores and/or barrier layers; drainage versions have their performance determined by transmissivity under load testing (ASTM D4716) and studies of geotextile permittivity/AOS and clogging (ASTM D4491, D5105) while barrier composites (geomembrane + GCL) require series-flow modeling and interface shear (ASTM D5321) to fulfill leachate collection and leak detection and dual-liner specifications(Koerner 2012).

Figure 4:Geocomposite

- **Geonet / Drainage Core**

The three-dimensional HDPE drainage core functions as a flow channel and its transmissivity-stress curves (ASTM D4716) and creep-compressed thickness (ASTM D6364) determine long-term flow capacity evaluations; when combined with geotextiles the system functions as leachate, gas or wall drains with filter criteria matching stand-alone geotextiles (Figure 5).

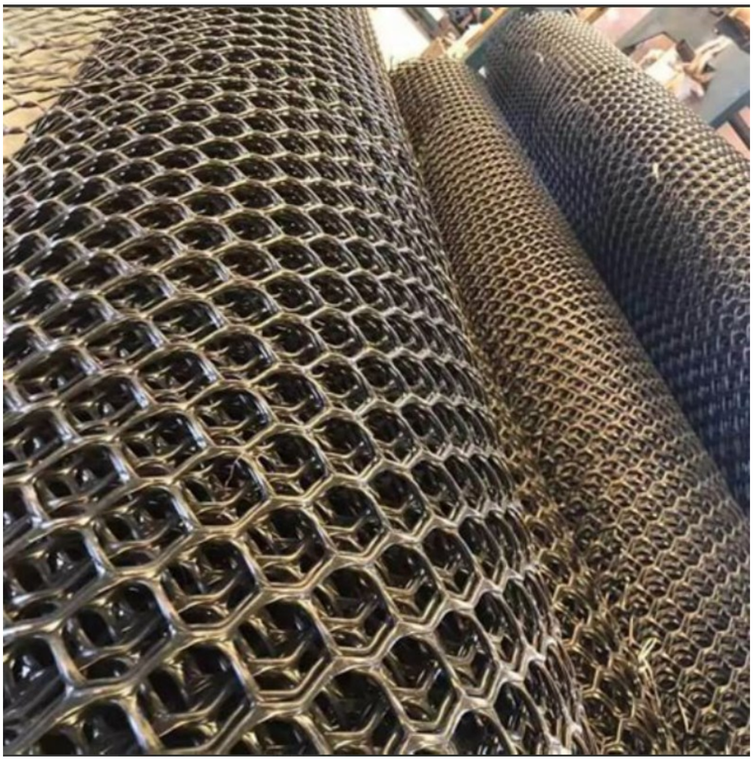

Figure 5: Geonet

- **Geocell**

The honeycomb HDPE/PP confinement system known as Geocell enhances both bearing capacity and apparent cohesion through elastic-plastic cell-infills that use ASTM D8269 creep data alongside ISO 10319 and ISO 13426-1 strip tensile and junction strength measurements and cell height/width ratios to design slope protection and retaining walls and load-support layers with deformation limits (Figure 6).

Figure 6: Geocell

- **Geotextile**

Permeable fabrics known as geotextiles (Figure 7) perform separation, filtration, drainage and light reinforcement by following hydraulic filter rules that require permittivity greater than soil k values and AOS values less than 5 times the d85 size with additional clogging checks (ASTM D5105). The mechanical design utilizes tensile modulus (ASTM D4595), puncture (ASTM D6241), and tear (ASTM D4533) to prevent rutting, tearing, and puncture in roadway separators, drains and erosion-control systems(D Cazzuffi et al. 2016).

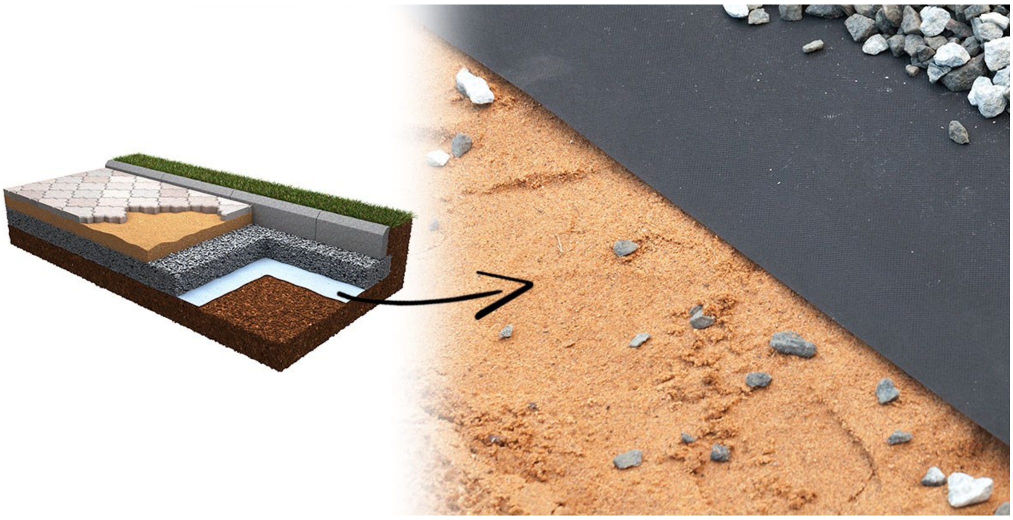

Figure 7:Geotextile

3.4 Environmental Applications of Geosynthetics:

Geosynthetics serve multiple environmental and geotechnical applications throughout various projects. The main application fields for geosynthetic materials consist of waste management (starting from landfills through mining tailings) coupled with water resource engineering (dams, canals, reservoirs) and coastal and river engineering practices and implementations in soil conservation. The implementation of such materials reveals enhanced operational results along with better sustainability levels when compared to conventional practices. A review of main application areas takes place within this part.

3.4.1 Waste Containment: Landfills and Mining Tailings:

Geosynthetics serve their first essential function by containing solid and liquid waste materials. All modern municipal solid waste landfills need geosynthetic liner systems according to current environmental regulations. A landfill base liner system usually consists of a primary HDPE geomembrane topped with compacted clay or GCL secondary layer and leachate collection functionality using geonet or drainage geocomposite (Dąbrowska et al. 2023). The liner system constitutes a powerful combination that effectively blocks leachate leakage. Research indicates that properly installed geosynthetic liners successfully contain over 98% of contaminants in the United States regardless of using composite liners (geomembrane+clay) or single geomembranes as long as leachate collection measures are present (Jain et al. 2023). Many years of field experience validate that geomembranes decrease contaminant movement to negligible levels. Geosynthetic clay liners enhance liner performance by healing small punctures automatically and absorbing differential settlements. Research conducted at Tehran's Aradkouh landfill in arid and semi-arid areas shows that geosynthetic liners successfully limit leachate production by stopping moisture from entering into soils according to (Jain et al. 2023). The implementation of landfill cover systems depends highly on geosynthetic components. The top layers of final covers use geomembranes or GCL barriers together with drainage geocomposites and erosion-control geotextiles to prevent rain infiltration and gas escape. A geomembrane installed in the cover fulfills dual purposes: it stops rain interference while enhancing landfill gas energy recovery potential. An example of this is using an HDPE geomembrane in landfill caps which both lowered infiltration levels and increased biogas outputs that enabled renewable energy production and allowed reduced cover thickness to add more waste. Drainage geocomposites within landfill covers substitute multiple layers of gravel to maintain slope stability through controlled runoff distribution thus providing reduced installation expenses than conventional soil drainsOld unregulated waste sites can be repaired through the use of geosynthetic materials that decrease pollution issues. The Cava de' Tirreni landfill in Italy established itself as a secure green space through implementation of a multilayer geosynthetic cap design during 2018 (Magazine 2022).

. The remediation procedure combined drainage geocomposite (MacDrain) for water drainage with GCL (MacLine) as infiltration blocker while adding a geomembrane-backed erosion control system (a “multicomposite” geosynthetic) to stabilize and protect the cover slope(maccaferri.com). The combination of geosynthetic materials resulted in efficient leachate prevention which led to the transformation of the site into natural vegetation while earning praise from local officials(Bianchi, Ghezzi, and Russo 2023).

Geosynthetics function as fundamental components for waste containment at MSW landfills and industrial along with mining facilities. Specific facilities utilize geomembranes or GCLs to cover the bases of mining tailings ponds thereby stopping heavy metals from leaking into groundwater(mdpi.com). The Canadian mining sector generates massive amounts of tailings materials and uses geomembrane liners as best practice standards for building new tailings containment facilities across the country (Chou, Brachman, and Rowe 2022). The 2021 review confirmed that modern tailings ponds use geomembrane liners to achieve enhanced seepage control when installation and puncture prevention measures are properly implemented (Tuomela et al. 2021). Geosynthetic covers are currently tested as potential tools for speeding up mine waste reclamation projects in oil sands tailings through floating combinations of geotextile and membrane systems that create fluid tailings caps and geotextile tubes for tailings dewatering and consolidation(Tuomela et al. 2021). Such vast tailings ponds remain hard to permanently seal but geosynthetic solutions will contribute significantly to future permanent solutions through procedures such as facilitating compaction and stopping water intrusion and water management tasks. Hazardous waste facilities together with industrial lagoons serve as areas where these applications are utilized. Specialized HDPE and PVC and bituminous geomembranes provide that use aggressive chemical environments for lining hazardous waste landfills and acid mine drainage ponds and petrochemical waste lagoons (Martins n.d.). The Porto Marghera petrochemical site adjacent to Venice employed composite geomembrane and GCL liners inside a containment cell to confine dredged sediments thus stopping leachate from contaminating the Venice lagoon according to environmental reports documented in 2020. Geosynthetic liners help constructions achieve full regulatory compliance by maintaining virtually no leakage in situations that demand strict protection for groundwater. Field research at Geosynthetic Institute shows that a geomembrane liner with any defect will leak substantially less with GCL or clay layers below it than a similar defect size in an unlined or single-lined containment structure and Geosynthetic systems produce fail-safe performance through their redundant construction method(Jain et al. 2023).

The application of geosynthetics has reached an indispensable level for waste containment systems. Geosynthetics function to protect the environment through leak prevention and simultaneously create economic value by using slender liners/covers while maintaining facilities' operational life. The implementation of geosynthetics materials in landfill construction has reached such success that most nations currently use them exclusively in their new facilities. As part of their leachate management programs Iran has equipped Kahrizak landfills alongside other major city waste sites around Tehran with geosynthetic liners as new construction or retrofit elements (Society n.d.). Geosynthetic liner systems are utilized as standard practice in waste landfills built during the 2020s that operate across the UK, US, Canada and Italy to fulfill EPA and EU regulations. Tests and historical performance data from decades along with present-day research on liners and stability shows that geosynthetic waste systems provide lasting safe waste containment (Yu and Rowe 2020)

3.4.2 Water Resources: Dams, Canals, and Reservoirs:

Water resource engineering utilizes geosynthetics to control seepage while restoring deteriorating structures in the field. The popularity of geomembranes continues to rise for their deployment as upstream defense liners on dams and protective sealing applications for canals and reservoirs and basins to reduce water leakages. Their quick deployment time along with superior impermeability makes them more attractive than the traditional thick clay blankets.

Embankment Dams:

Since the 1970s geosynthetics have become an integral part of embankment dam construction (Arefpanah, Sharafi, and Salehi n.d.). The current practice entails geomembranes as a solution for extending the lifespan of leaking concrete or masonry dams. The rehabilitation of a large Italian masonry dam involved implementing an upstream PVC geomembrane system which rested on a cushion geotextile to stop seepage that traditional grouting methods could not control (Daniele Cazzuffi, Gioffrè, and Luciani 2023).The Karaj Dam in Iran underwent renovation through a geomembrane bonded to a heavy nonwoven geotextile that minimized seepage while lengthening its operational lifetime (Dams 2023). Earth dams contain geotextile filters for safe filtration of seepage water which prevents the internal erosion process known as piping. Iranian engineers evaluated the filter performance of geotextiles in embankment dams through their studies which proved that properly constructed nonwoven geotextiles meet filtration standards and permeability needs to substitute extensive sand filters. The research on dam filter design establishes that geotextiles serve as effective filters for fine soils when using robust testing standards such as those from German BAW or ISO Smart geosynthetic technologies with built-in optical fiber sensors embedded behind geomembrane liners detect leakage positions through alterations in signal output while being tested in dam applications. The implementation of these technological systems enables continuous observation of dam operational health conditions (Arefpanah, Sharafi, and Salehi n.d.).

Canals and Reservoirs:

Geosynthetic liners demonstrate exceptional value when used to line both canals and artificial lakes especially within arid regions. The Chitgar Lake in Tehran, Iran exceeds 130 hectares because engineers installed an entire HDPE geomembrane layer on its 100% permeable ground surface to prevent water loss (KHEZR SEDDIGH MAZINANI and RAFIPOUR 2014). This lake finished its construction during the late 2010s and its official name is the Persian Gulf Lake. The structure required the geomembrane to retain water because of the permeable ground. Following the installation of the geomembrane the project developed into a resilient recreational water feature and secured ground water from runoff contaminants. Irrigation canals throughout California now save substantial water in delivery by using geomembrane settings which have their surfaces protected by concrete or soil layers. Water deliverability by geomembrane-linen earthen canals has been found to enhance by 30–50% based on research (Akhavan et al. 2024). Geosynthetics have become standard materials for enhancing water conservation by relining previous US West, Indian, and Middle Eastern canals within five years under World Bank and governmental programs.

Ponds and Lagoons: Geosynthetics provide benefits to wastewater and potable water lagoons along with ponds. Wastewater ponds within industrial facilities employ double-liners made from geomembranes and GCL components connected by leak detection geonet systems to stop the release of contaminants (Dąbrowska et al. 2023). Mining facilities which use pregnant leach solution in heap leaching operations or evaporation water reservoirs depend on geomembranes with chemical resistance for their process ponds. Scientists currently investigate the long-term performance of specialized geosynthetics (including bituminous geomembranes and EPDM liners) when exposed to harsh chemical environments through multiple research studies published during 2020–2022 and Reducing severe conditions as well as correct formulation with antioxidants and UV stabilizers and regular inspections can extend HDPE geomembranes towards a lifespan spanning decades. (Martins n.d.)

Water projects use geosynthetics as an efficient construction tool which results in minimal maintenance needs. The implementation process of geosynthetic liners outperforms clay-lined reservoirs because it takes only a fraction of the time and less material while builders install these systems. The GCL+geomembrane system used at a Polish reservoir fixed the damaged original clay core after drought through a quick installation process that successfully capped the reservoir. Under conditions of varying water levels geosynthetics preserve their flexibility properties. The ability to withstand differential settlement and rapid drawdown without cracking (which clay is unable to provide) makes these liners highly valuable because of their effectiveness in changing climate conditions(renupublishers.com). Nonwoven geotextiles and geomembranes inside German flood retention basins act as interior liners for managing quick filling and emptying operations which traditional liners cannot withstand. Water resource infrastructure uses geosynthetics as standard construction materials because they deliver dependable outcomes and optimized performance. The seepage control sector consists mainly of geomembranes and GCLs in dams and canals and ponds and reservoirs worldwide. Data collected in 2021 from over 70 embankment dams confirmed that geosynthetic systems decreased seepage while enhancing safety at every location and prevented all cases of geotextile-related internal erosion (Arefpanah, Sharafi, and Salehi n.d.).Geomembranes simplify canal maintenance because one can easily fix punctures yet fixing concrete material requires much more effort. Geosynthetics remain essential components of water management projects since their performance advantages make them key to water conservation work and infrastructure rehabilitation during limited budget times.

3.4.3 Erosion Control and Soil Stabilization:

The environmental defense against sedimentation and land degradation becomes possible through geosynthetic materials which prevent soil erosion and stabilize slopes. Erosion control mats and geotextiles constitute standard protection elements for steep slopes together with riverbanks and coastal shorelines. The repair process for newly constructed slopes involves temporary protection by biodegradable natural fiber materials like jute and coir mats before vegetation establishment while synthetic turf reinforcement mats with geocells provide long-term protection against high shear stresses . In India and Bangladesh coir and jute geotextile blankets exhibit successful use for protecting riverbanks through their degradation process which allows grasses to take root and stabilize the bank on their own(Khattra and Jain 2024). Research findings demonstrate that these natural-fiber geotextiles minimize slope soil runoff and erosion losses by 50% or better than bare soil alone. Such materials are inexpensive yet biodegradable and they can be obtained through local supply chains so they match sustainable practice requirements. Slopes or shorelines with difficult erosion prevention demands get protected using geocells together with high-strength turf reinforcement mats (TRMs). Soil placement within geocell three-dimensional honeycomb grids allows polymer strips to form confinement pockets which enhance the soil's ability to resist erosion and sliding. Geocells added to a 45-degree slope in Virginia, USA maintained a vegetation cover alongside preventing washouts in extreme rainfall conditions according to research in 2022 while an unreinforced control slope underwent minor landslides (Hossain, Hoppe, and Weaver 2019; Martins n.d.). also Full-scale impact tests on 4 m-high geogrid-reinforced earth berms have shown that these composite barriers can safely dissipate >3 MJ with deformations < 1 m, confirming their suitability where wire-net fences reach their limit (Ronco, Oggeri, and Peila 2009).

Discrete-element back-analyses replicated measured face displacements within ±10 %, underpinning a first-cut energy-vs-berm-height chart for preliminary design (Oggeri, Ronco, and Vinai 2021). Protective slopes and channels receive their support from TRMs which are enduring synthetic mats typically constructed from polypropylene that provide root integration. These mats provide drainage channel lining as an alternative to riprap when high stormwater velocities exist and function to stop channel scour and enable vegetation growth(Martins n.d.)

3.4.4 Environmental Use of HDPE Geomembranes in Slurry Walls

HDPE geomembranes serve as a vital component of vertical barrier systems for environmental engineering when used in cement-bentonite or slurry diaphragm walls. A vertical placement of HDPE geomembrane inside slurry trench walls serves to enhance both the hydraulic performance and chemical resistance.

These combined cut-off walls provide superior polluted site cleanup and groundwater protection through the combination of cementitious materials' self-healing properties and HDPE's impermeability. The geomembrane serves as the primary impermeable component yet mechanical support and installation arise from the adjacent slurry or concrete walls. The combined design approach meets strict environmental standards while it significantly reduces permeability and controls the movement of leachate or hazardous chemicals alongside other substances(Nguyen et al. 2021).

3.4.5 Contaminated Site Remediation and Other Applications

The remediation of polluted sites through brownfields and mining territories and industrial lagoons uses geosynthetics to provide physical barrier separation for pollutant isolation. The installation of geosynthetic caps on contaminated soil stops both rain penetration and vapor migration. A decommissioned chemical factory site in Ontario Canada received geosynthetic cap installation that included a gas venting geocomposite followed by an HDPE barrier membrane and surface drainage geotextile (Dąbrowska et al. 2023).Geosynthetic materials enabled site development as a parking facility through minimal soil excavation because of their protective capabilities. The Superfund landfill located in New Jersey (USA) received a geosynthetic clay liner followed by a geomembrane treatment during the 2020s before the installation of the Gloucester GEMS Landfill Solar Plant on its surface. (Beauregard and Budge 2025) recognized this winning project which demonstrates how geosynthetics enable the combination of sustainable development practices with environmental remediation work. Geosynthetic materials find specialized applications in bioreactor landfill waste management through liquid circulation features and airflow piping and also provide odor control through wastewater tank floating membrane covers and protect groundwater during manure lagoon lining activities. Geosynthetic materials are applied in cold regions as insulation covers for polluted tailings to lower the effects of permafrost thaw as illustrated in (Han and Jiang 2013).

Disaster relief and temporary works depend fundamentally on geosynthetic materials for their development. Sand, soil and rocks can be rapidly stabilized and temporary barricades established by employing geosynthetic materials in the aftermath of earthquakes and storms. Engineers constructed a geosynthetic-reinforced earth dam as a rockfall barrier after a severe rockfall event in Asia by building geogrid and soil layers into a dam structure which arrested further rock movement safely (Pietro Rimoldi et al. 2021). Such emergency infrastructure demonstrated faster construction than traditional concrete walls because it utilized geogrids to reinforce onsite fill materials thus demonstrating geosynthetics' quick response capabilities during times of need. Every sub-discipline of environmental and geotechnical engineering relies on the broad use of geosynthetics. Different environmental applications emerge annually which demonstrate how geosynthetic materials have become vital construction tools for civil engineers dealing with environmental dilemmas. This subsequent segment can provide regional case studies about implementations within Iran and the USA followed by assessments of the UK, Canada and Italy.

3.5 Regional Case Studies and Variations

The basic applications of geosynthetics remain identical globally but nationwide demands and local conditions determine specific implementation methods. This portion includes at least three contemporary case studies and applications of geosynthetics in each targeted region including Iran, US, UK, Canada, and Italy so as to illustrate their extensive utilization patterns alongside regional-specific developments.

3.5.1 Iran:

Case1: The arid conditions of Tehran demand that Lake Chitgar receives geomembrane lining protection. The creation of Chitgar Lake mentioned as Iran's biggest artificial lake at ~130 ha needed geosynthetics for its successful implementation. To stop underground leakage of water the lake bed received a complete HDPE geomembrane lining with 2 mm textured surface (Society n.d.).Feedability studies revealed that alluvial soil would not retain water because the geomembrane lining was absent. The installed geomembrane achieved successful sealing results since welding took place onsite during 2012–2013 resulting in minimal water level changes due to evaporation except for the period. The completed 2018 development transformed an empty wasteland into an aquatic recreational site with wildlife protection through its implementation of geosynthetic materials that promote extensive water infrastructure development in regions with water scarcity. The installation of the liner safeguards groundwater from pollution threats entering through urban runoff drainage (since urban runoff discharges into the lake). The success achieved in Chitgar Lake has ignited Iranian interest to apply geomembrane lining technology for different types of water storage facilities such as irrigation reservoirs and aquaculture ponds.

Case2: The city of Tehran pursues geosynthetic reinforced soil structures as part of bridge abutments to enhance seismic resistance while lowering construction expenses. The Milad Tower Boulevard in Tehran received its first large GRS abutment construction when the project was finished in 2009 (Mirlatifi 2012). During the past five years the method gained increasingly widespread applications. The 2021 Tehran-Shomal Freeway project made use of geogrids (Polyester uniaxial) for maintaining several high reinforced soil walls alongside abutments that stabilized approach fills on soft ground terrain. Underloading conditions on the Milad abutment instrumentation revealed minimal structural deformations and the tower's nearby seismic events caused no damage to the structure. The geogrid solution proved cost-efficient since it reduced expenses by thirty percent compared to traditional concrete abutments through its use of deep foundations and local backfill. The design reduced both traffic interferences and logistical burden from material transportation within cities. Studies from Iran demonstrate the same results observed worldwide that geosynthetic-reinforced abutments create beneficial outcomes under static and seismic loads while producing lower carbon emissions because they reduce concrete and steel usage (Rajabian, Vahedifard, and Leshchinsky 2024). Rate of success is now starting to address local uncertainties and insufficient knowledge about these applications as noted by Iran's IGS Chapter through their educational outreach efforts for designers.

Case3: Engineers established geotextile tubes as coastal protection measures at Qeshm Island because the Persian Gulf coast suffers from erosion while rock resources are limited for conventional breakwaters there. Engineers constructed a geotextile tube breakwater in 2020 to defend the Qeshm Island public beach shoreline. (Shabankareh, Ketabdari, and Shabankareh 2017) conducted a study which described the offshore placement of two parallel geotextile tubes (each 2.5 m diameter) filled with sand. The environmental research determined the performance of a nearby conventional rock breakwater at Bushehr against this solution. The installation of geotextile tubes as a sand-filled barrier offered multiple benefits including shortened construction time and small disturbance area on the seabed and local dredged sand use for filling purposes (reducing quarrying needs). Results from post-monsoon monitoring demonstrated that the geotube breakwater accumulated wave dissipation and the calmer waters behind the tubes began to be filled with mangrove saplings which provided ecological value (academia.edu). A review examination showed the geotextile suffered minor wear although the system remained in proper condition. That required fabric durability improvements and UV protective material over the structure. Geosynthetics have seen increased implementation for coastal engineering applications in Iran because of the domestic production of durable geotextiles produced in the recent years. The protective measures follow governmental strategies that support maintaining natural coastal views and preserving ecosystems.

Iran applies geosynthetics technology throughout urban development activities to seal foundation pits in Tehran using geomembranes while blocking seepage from sandy soils and utilizes geosynthetics in landfills through liners and covers as well as in irrigation projects with geotextiles to limit soil salinization. The Iran Chapter of the International Geosynthetics Society predicts that the maximum potential for geosynthetics implementation exists through applications in highway/railroad structures combined with drainage elements and water and erosion protection operations. Recent experiences show geosynthetics contributed to the development of significant waterproofed lakes in addition to cost-efficient bridge supports and environmentally friendly coastal defense systems in Iran since last few years despite facing brief obstacles in persuading conservative clients to embrace revolutionary geosynthetic solutions(Society n.d.). The local universities together with local companies actively conducting geosynthetic research and manufacturing create strong potential for Iran to deploy geosynthetics throughout infrastructure and environmental projects.

3.5.2 United States:

Case1: A Geomembrane-Lined Landfill in New Jersey now serves as a solar energy project under the Solar Energy Cap program (New Jersey). The Gloucester Environmental Management Services (GEMS) Landfill in New Jersey functions as a leading example of a Superfund site. The early 2000s installation of a multi-layer geosynthetic system featuring clay and HDPE geomembrane and drainage layers and vegetative soil on top stabilized the 60-acre landfill and controlled environmental risks. This cap made it possible to deploy a 19-acre 4.5 MW photovoltaic array since the geomembrane effectively separated the waste from outside elements making pile foundation and heavy ballasted systems unusable for liner protection. A new patented ballasted racking system spread weights across the cap without damaging its integrity. The operational solar power system demonstrates how a geomembrane landfill cap can convert previously worthless territories into profitable landfills that protect environmental integrity(Advanced Textiles Association n.d.). The HDPE cap demonstrates superior performance since it has maintained its effectiveness for about twenty years and landfill gas conditions have remained stable during solar construction.The case demonstrates that geosynthetics provide dual advantages through environmental protection and sustainable socioeconomic benefits such as clean power generation for landfills throughout the United States (Ciriminna et al. 2018).

Case2: Geotextile-Reinforced Dune and Breakwater System in Louisiana operates as a protection mechanism for Coastal Louisiana where erosion and land loss become serious through the effects of hurricanes. The use of rock and clay methods as traditional solutions becomes impossible to implement on the soft deltaic soils. The prevention of wetlands at the Cameron Creole Coastal Refuge in Louisiana through the installation of breakwaters fortified with geotextiles became reality in 2021. The conceptual design implemented geotextile-bound sand-filled structures as breakwater components which contained high-strength geotextile-wrapped lightweight aggregate as supporting berm base materials. The designers selected expanded clay balls as lightweight aggregate because they minimize settlement effects in weak subsoil. The implementation process included placing geotextile-encased aggregate solidified with sand in the structure before finishing it with local rock distribution. The hybrid geosynthetic-breakwater received close observation during testing. Per available data the installation resulted in “dramatic results” since wave energy at the marsh edge decreased substantially while wetland vegetation started to appear beyond the breakwaters area. The geosynthetic solution addressed regional construction difficulties because it survived shoreline adjustments without failure while producing much lower settlements than traditional rock structures would have. The coastal engineering project demonstrates precisely how American specialists use geosynthetics to create designs appropriate for ultra-soft soils while accomplishing ecological missions. The U.S. Army Corps of Engineers routinely includes geotextile tubes and geocells and marine mattresses in coastal restoration operations throughout Mississippi and Texas to construct strong "living shorelines." The Louisiana example showcases how synthetic and natural elements can build efficient shoreline defenses that preserve coastal habitats in ways that match current nationwide developments in nature-based solutions (L.Reid 2021).

Case3: The implementation of geogrid base reinforcement supports infrastructure development through marshland areas represented by the Seattle Washington project. A road development project in Seattle's Montlake neighborhood executed its construction across a damp marsh area where water rose high. The engineers settled on an embankment made stabilized by geogrid which avoided the need for extensive excavation of the peat layer. A separation geotextile covered the marsh surface before engineers installed a Tensar uniaxial geogrid which received fill layers with additional geogrid to establish the stable base design (D. Wang et al. 2023)This engineered solution managed to distribute weight loads which prevented settlement differences along with fill contamination of soft soil beneath it. The project succeeded through geosynthetic implementation because it restricted grading fill requirements to just their essential volume (instead of requiring the full replacement of peat). Construction went ahead with lower expense and reduced environmental impact because adding the geogrids decreased the construction footprint and minimized dewatering needs. Because the geosynthetic solution protected the local ecosystem this gained high value in the permitting process. Inspection surveys confirmed that during the wet season the design showed minimal ground settlement at the construction site. Geogrid technology allows engineers to construct infrastructure on weak and environmentally sensitive soils throughout the United States by providing effective support. Examples of this method include installations in Florida wetlands and Alaska permafrost regions. Geosynthetics enable engineers to build infrastructure structures above sensitive terrains while keeping any disturbance at a minimum in order to meet rigorous environmental standards(Alec Anderson 2022). Modern geosynthetics prove their worth in urban projects through design methods validated by field evidence demonstrating their ability to stabilize soft ground. This aspect is demonstrated particularly well in the Seattle project(Blackwood and Vulova 2006).

The widespread usage of geosynthetics across the United States includes landfill lining applications because of Subtitle D regulations while transportation and coastal projects are more frequently incorporating them due to combined performance and sustainability targets. Several federal alongside state government agencies including FHWA and EPA along with FEMA now use geosynthetics within their engineering regulations. The Federal Highway Administration's design manuals list geogrid/base reinforcement as a pavestone design option after documenting extended service periods achieved at reasonable extra costs. The US Environmental Protection Agency supports implementing GCLs and geomembranes for brownfield caps and covers through risk-based remediation methods. Engineered Turf Covers (ETCs) demonstrate successful applications in U.S. industry through their use as synthetic grass tops on geomembranes which resist wind and enable solar installation as shown by an ETC system in Texas surviving 100+ mph winds during a 2020 storm (Alec Anderson 2022). The American geosynthetics market presents a mature and dynamic environment which shows promise for sustainable infrastructure development via drainage systems for green roofs and hurricane-resistant coastal barriers through the use of geotextile tubes. The United States demonstrates multiple global benefits of geosynthetics by reducing costs while accelerating construction and boosting infrastructure durability while ensuring environmental protection compliance in numerous Alaska to Florida projects and beyond (Dąbrowska et al. 2023).

3.5.3 United Kingdom:

Case1: The Environment Agency of the UK introduced Thorpeness (England) coastal erosion control through sand-filled geotextile bags as part of its softer coastal defense research. A collaborative effort with local authorities and residents resulted in installing large geotextile sand containers that served both to protect the dunes at the toe as well as offshore protection measures. These sand-filled units measured approximately 2-3 meters cubed in size. Naue GmbH engineered durable geotextile bags which received beach sand fill for the creation of artificial dunes and nearshore breakwaters in their targeted positions. The sand-filled bags installed in the protection measure have shown substantial success in lowering shoreline erosion since they disperse wave energies instead of affecting the natural beach behind them. Protection of natural coastal characteristics remained possible through this initiative because the bags became integrated with the beachway when the sand covered them and beachgrass grew over them. From both aesthetic and ecological standpoints the usage of sand-filled bags produced better results compared to building rock barriers or concrete walls along the coastline (Jones et al. 2023). The geosynthetic system incorporates features for maintenance because teams can easily fill or relocate damaged or displaced bags after storms. The approach shows early positive outcomes which makes it suitable for replication across UK sites that seek protection together with natural aesthetics. People from Thorpeness have embraced geosynthetics as an alternative for coastal protection through their community-led funding effort which demonstrated their confidence in these “soft engineering” approaches designed by engineers.

Case2: The rail sector of Scotland uses geogrids together with geotextiles to stabilize slippery embankments which exist from old tracks that become unstable due to rainfall. Railway embankments on weak glacial soils in Scotland received high-strength geogrids and geocells reinforcement treatment recently during the year 2020 along the West Highland Line. Network Rail contractors deployed several layers of Tensar RE geogrids together with compacted fill to develop a reinforced soil foundation which impedes minor landsliding occurrences. A biodegradable coir matting was introduced to the surface area before seeding began to assist immediate vegetation growth. The installed system managed to stop all further slidings during heavy rainfall in 2021 before the vegetation completely covered the geogrids by summer 2022. The 2022 Ground

Engineering magazine highlighted the sustainable nature of this solution because it reused local soil instead of incurs the carbon emission costs associated with adding concrete or extensive rock material. Sediment from landslides successfully stayed out of the vulnerable waterways which served as salmon spawning grounds for that area. Geosynthetic reinforcement has become a critical solution for Victorian-era rail embankment remediation in the UK because Network Rail has developed guidelines for geotechnical asset management that contain geogrid recommendations. The case demonstrates how British infrastructure owners successfully expand their asset lifespan by using geosynthetics while meeting environmental boundaries through vegetative slopes which perform better than standard retaining walls from both performance and environmental perspectives (Siino 2022).

Case3: Landfill Remediation and Reuse (Southampton, England) demonstrates how the UK uses geosynthetics as the main component in their plans to close closed landfills according to EU Landfill Directive requirements. The Netley landfill near Southampton received its cap treatment for public green space conversion from 2019 to 2022. The landfill cap incorporated a geosynthetic clay liner (GCL) with a polyethylene geomembrane as the main barrier system that was covered by a composite drainage net/geotextile structure for leachate ventilation and rainwater drainage. The geosynthetic barrier system prevents all rain intrusion which is essential for the landfill location because it faces sensitive estuarine wetlands. Independent monitoring data indicated that the geosynthetic cap systems successfully removed rainfall from the site during heavy 2020 storms because leachate levels remained unchanged in the observation wells. Reducing the site's contamination risk has been achieved through this method. After finishing the cap installation process soil and vegetation were applied to surface areas permitting incorporation of the site within Royal Victoria Country

Park boundaries. The Netley Landfill capping project resembles various landfill cap installations throughout the United Kingdom including the Freshwater landfill in Isle of Wight and the Dargavel former oil shale bing in Scotland. Geosynthetics form the enabling solution for the conversion of landfills into parks because they guarantee both continued containment of waste materials and boundary contaminants along with surface capability to support grass growth and pathway infrastructure (local geogrid usage included for path reinforcement). Implementation of a geosynthetic gas venting layer during the Netley project demonstrated how geosynthetic systems enable complete environmental management in landfill remediation(Dąbrowska et al. 2023; Jones et al. 2023).

The UK's geosynthetic practices heavily depend on regulatory requirements that prompt engineers to adopt advanced solutions when securing sites while reusing available land. Geosynthetics can be observed in nearly all newly constructed highways as separator materials within pavement layers and basal reinforcements of embankments built on soft alluvium sediments including the Queensferry Crossing approach embankments finished in 2017 which benefited from geogrid conservation approaches. Following the 2014 devastating floods the Somerset Levels received fixes to river embankment breaches through the application of stone columns wrapped in geotextiles to strengthen foundations before levee reconstruction illustrated successful integration of original materials combined with geosynthetic assistance. The UK's Highways England along with the Environment Agency routinely release research about geosynthetics which specifically demonstrates that geomembrane cut-offs embedded in levees minimize seepage below the acceptable levels and so these should be implemented for future levee upgrades (2022). The UK maintains its position as a worldwide pioneer in geosynthetic adoption because it needs to optimize performance and land use efficiency combined with the rigorous environmental objectives of carbon reduction and biodiversity net gain fulfillment. The utilization of geosynthetics serves to improve these outcomes by using less building materials as well as making possible environmentally friendly solutions such as living shorelines and vegetated reinforced slopes (Khattra and Jain 2024)

3.5.4 Canada

Case1: The railway over Permafrost rehabilitation project at Churchill in Manitoba was implemented following the 2017 flooding which devastated the remote line because of permafrost thaw. Geosynthetic reinforcement through NPA geocells was employed during the 2019 innovation stage to stabilize ice-rich tundra underneath the rail embankment . The project used two layers of Novel Polymer Alloy geocells with lower layers containing crushed rock as stabilizing mattresses while upper layers received ballast material. The geocell solution distributed the track loads and suppressed differential settlement to enable track reopening before embankment reconstruction completed or while the area remained inoperative until winter deep ground freezing. Future climate changes will be managed through geocell reinforcing elements since they spread stresses during settlement while rigid structures would likely break. The case has emerged as a Canadian benchmark solution for adapting infrastructure to deal with climate change effects. The application of geosynthetic solutions enabled rail line maintenance according to Federal transportation reports which otherwise would have sparked the need to either abandon use of the rail line or perform very expensive modifications. Geosynthetics helped save the lifeline of the railway by showing resilience to the environment(Sanat Pokharel and Marc Breault 2021).

Case2: The Alberta Oil Sands industry executes trials for reclamation of vast tailings ponds through Tailings Pond Closure Test Cover methods. The Base Mine Lake at Syncrude features a geosynthetic system as part of its pilot project. In 2020 laboratory personnel placed a geosynthetic cover system on a section of tailings pond by firstly using wick drains followed by high-strength geotextile layers then adding a geomembrane liner with sand on top to achieve dry closure conditions. The geotextile functions as a wick drainage system to dehydrate tailings and creates a stable foundation for the liner while the geomembrane stops rising moisture. The wick drain system works in combination with the system to remove water while pushing drainage forces through the drainage wicks. The initial two-year study revealed tailings settlement under the test cover demonstrated positive movement of consolidation as well as an unharmed liner system. Through upscale implementation of geosynthetic capping systems engineers can transform big water retention pits into suitable landscapes by re-vegetation methods much more quickly than conventional settlement processes. Geosynthetics serve as a groundbreaking technology to repair oil sands tailings in their natural position despite these materials being notoriously hard to remedy. The successful results of this Canadian trial suggest geosynthetic materials have the potential to serve as a crucial solution for a major environmental clean-up effort throughout the country. The technology presents Canadian advancement of integrating drainage and containment geosynthetics into new applications (Paulsen 2025).

Case3: A mining operation in BC built the very high geosynthetic-reinforced soil (GRS) wall during 2021 as a basic element for mine waste containment and ore processing platform development (British Columbia). The wall installation involved up to 30 meters of height and 100 meters of length. The construction team utilized structural layers of PET geogrids and steel mesh facing materials (also known as “Geosynthetic Cementitious Composite Mat” facing). This structure functions to contain mine waste while standing on a mountainside and designers prepared it to withstand seismic activity and abundant rainfall. The implementation of geogrids made it possible to construct this project at a steep near-vertical angle thus limiting the required mountain site area while reducing needed rock removal. This geogrid wall ranks among the highest type in the entire continent of North America. Geo-monitoring devices placed inside the wall including extensometers and inclinometers confirm the predicted stable design performance. Implementing geosynthetics resulted in savings of 50% compared to other solutions such as concrete retaining walls or earth dam embankments that would be required normally. The incorporation of mine waste rock as fill inside the geogrid structure achieved resource management by reducing quarrying operations. Within Canadian mining operations geosynthetic reinforcement stands as the preferred choice for building retaining structures at tailings and waste facilities because it provides both superior safety through its flexibility and drainage functions and reduced costs(Mirlatifi 2012) . The 2014 Mount Polley tailings dam failure in British Columbia triggered increased examination regarding stable conditions of mine waste structures.

Different geosynthetic applications in Canada serve to address key environmental elements including northern permafrost areas and river valley soft alluvial soil conditions as well as vital water security needs. Canadian highway departments have been utilizing geotextiles for drainage applications and separation functions since the 1970s after installing them in a road constructed on Quebec peat soils. The sustainability approach has become prominent in recent Canadian projects because they demonstrate how geosynthetics help reduce environmental impact. A 2021 life-cycle assessment from Ontario’s Ministry of Transportation discovered that roads constructed with geogrids cut down greenhouse gas emissions by approximately 30% because they needed reduced aggregate sources and transported fewer trucks. pursue the integration of recycled polymers into geogrids and geocells while advancing circular economy principles by developing waste material-based products which already exist as PET bottle-containing commercial products. Geosynthetics serve as environmentally sound solutions in Canada because they fulfill national sustainability objectives through material conservation, water protection systems and infrastructure adaptations to address climate changes (Charpentier, Fourmont, and Allaire 2024; Giroud et al. 2023). The investigative research in Alberta and British Columbia road projects exemplifies these predominant themes (Huang et al. 2025).

3.5.5 Italy

Case1: The Capping of Cava de' Tirreni Landfill (Campania) and Ecological Restoration project takes place in Italy yet remains subject to European Union directives which specify landfill remediation. The Cava de' Tirreni landfill in southern Italy received inadequate closure during the 1990s thus leachate escaped through improper containment and polluted water resources. An extensive project started in 2018 to protect and top this landfill with geosynthetics thus creating a green zone from it. The complete solution adopted several geosynthetics including the MacDrain geocomposites along with the MacLine GCL (bentonite clay liner) and geomembrane for impermeable barrier functions and the ParaLink geogrids joined with the Terramesh geogrid wrapped-face system to strengthen cover soils on steep side slopes. The complete geosynthetic system operated as an integrated solution where it combined features to maintain waste containment while draining out rainwater and landfill gas and supporting soil slope stability and offering protection against surface erosion. The installation resulted in such low toxic leachate production that the landfill became virtually inactive while the Bonea stream water quality dramatically improved. The surface was successfully revegetated, effectively turning a toxic dump into a “small green lung” for the community The project also reported a substantial reduction in carbon emissions compared to a traditional clay-only cap: the geosynthetics reduced material transport and construction time, which minimized CO_2 emissions and worker exposure risk during construction.This acclaimed project (featured by the International Geosynthetics Society in case studies) showcases Italy’s advanced use of geosynthetics for environmental remediation. The multicomponent geosynthetic system represents the "geosynthetic toolbox" method of handling complex engineering issues. As Italy moves through the 2020s it remediates former landfills to EU standards while achieving many closures that represent the Cava de’ Tirreni test case. The implementation of geosynthetics enables engineers to conduct reliable projects at fast installation rates on complex locations where landfills often exist (Magazine 2022)

Case2:

Geosynthetics find extensive application for underground waterproofing operations throughout Italy especially within metro tunnels and transit networks in Milano city. During its completion year of 2022 the new Milan Metro Line 4 utilized extended geomembrane waterproofing along all its tunnel and station areas. A PVC geomembrane was installed as a continuous waterproofing layer between the primary and secondary linings, compartmentalized with waterstops into sectors of ~150 m^2 This compartmentalization with geosynthetic waterstops is crucial – it localizes any leak and allows for targeted injection repairs behind the membrane if needed.In fact, this method was pioneered in Italy (notably used in older Milan and Rome metro lines) and has been further refined: Milan Line

4 uses a double-layer geomembrane system in particularly critical zones, with two membranes sandwiching a monitoring gap.If the inner layer leaks, the outer layer still stops water, and the interstitial space allows pinpointed injection to seal the inner tear.This advanced geosynthetic application ensures the underground structures remain dry and durable, preventing issues like water ingress that plagued some mid-20th-century tunnels(Daniele Cazzuffi, Gioffrè, and Luciani 2023).

Case3: Geogrid-reinforced slope stabilization becomes crucial for Italy because its rugged Apennine landscape continuously subjects slopes to landslides. Slope rehabilitation along with landslide repair employs geosynthetics as an accepted method. Geogrid-reinforced soil bunds and drainage geocomposites stabilized a chronic landslide in 2020 at the Bologna location along the A1 Autostrada in the Apennines Mountains. By excavating benches into the slope the design included the placement of tensile-strength-holding high-strength polyester geogrids before rebuilding the slope through compacted layers which formed a reinforced structure that supported the landslide material.. The project team installed vertical wick drains together with a geocomposite drainage layer to decrease pore pressure effects. The implementation of geogrids made it possible to keep most landslide soil where it originally rested rather than extracting large volumes. Post-heavy rain inclinometer monitoring resulted in minimal slope movement which proved the effectiveness of the adopted technique. The project attained importance because its reinforced slope reached a height exceeding 20 m while preventing repeated closures of the major highway. Environmental sensitivity showed through the project because site soil reuse together with limited riprap and concrete imports decreased the overall ecological impact. Complete vegetation covered the slope which returned its natural landscape appearance. Italy utilizes numerous reinforced slopes as a highway safety measure which includes the Firenze-Bologna high-speed rail line that uses geocell and geogrid to stabilize clay shale cuts. Italian professional practitioners amalgamate geosynthetic reinforcement strategies with bioengineering methods which include live stake planting and hydroseeding procedures on geojute mats to deliver slopes that match natural landscapes while maintaining engineered stability(Khattra and Jain 2024).

Geosynthetic materials play a widespread role in Italy's soil stabilization efforts within landslides and serve as retaining elements and as a replacement for concrete gravity walls in mountainous areas and support both landfills and reservoirs and dams. Italian engineering teams now employ geosynthetic cementitious composite mats (GCCMs) as drainage channel and slope linings through their ability to transform into hardened concrete after hydrating the cement impregnated geotextiles. Applications of poured concrete began since 2018 in erosion control operations including bank canal liner installations for the Arno river. The new alternative technique replaced traditional concrete construction. The research activities in geosynthetics receive exceptional emphasis in Italy as reflected through the 12th International Conference on Geosynthetics which was successfully held in Rome during 2023. This event showcased Italian innovations based on sustainability as well as new material applications. Italian standards (UNI) share conformity with EN ISO geosynthetic standards to provide complete high-quality design and testing methods. Geosynthetics enable Italy to handle the problems created by both historical waste disposal sites and ancient built environments and its difficult natural terrains. The versatile nature of geosynthetics enables Italian engineers to adopt them as default solutions when developing dry protective systems for metro tunnels and moisture barriers for landfilled parks and landslide prevention measures for vineyards. The investigated regional examples reveal how geosynthetics meet both functional requirements and local needs through retention of distinctive landscapes and heritage properties together with compliance with neighborhood requirements regarding safety and visual appeal.

For example, Tunnel-portal slopes in Piemonte have been successfully stabilised with steel-mesh + anchor lattices; vibration monitoring during excavation kept PPV < 25 mm s^{-1}, avoiding traffic disruption [(Greco and Oggeri2 2004)].

Italy's dedication to environmental sustainability as well as “il territorio” preservation makes such efforts fit perfectly with its objectives.(Bianchi, Ghezzi, and Russo 2023; Kraus 2022).

CHAPTER 4: EXPERIENCES AND CRITICAL KEY POINTS

4.1 Introduction:

Geosynthetics have developed from niche polymer fabric to the heart of sustainable environmental infrastructure. This chapter draws together a quarter-century of global field evidence and peer-reviewed research to shed light on how these materials provide reliable containment, water conservation, erosion control, and ground improvement in various climates and regulatory environments. It explains the critical factors, composite action, interface behavior, quality assurance, and material durability, by interlacing practical case histories and quantitative performance data. The narrative also outlines the frontier of biodegradable and sensor-enabled products, providing a framework for future research yet providing a sound knowledge base for practitioners and policymakers alike. in this section the Experience refers to documented field performance, forensic audits, and case histories. Critical Key Points represent the lessons that have been distilled down directly to affect design, construction quality assurance/control (CQA/CQC), regulation, and future research which A systematic review protocol case studies across five climatic and regulatory regions (USA, UK, Quebec/Canada, Iran, Italy).

4.2 Cross-Cutting Performance Themes

Geosynthetics exhibit a range of overarching performance behaviours that are repeated regardless of project scale, climate, or regulatory environment. The five themes distilled below synthesise the most consistent lessons gleaned from the literature review and field case histories and provide a practical framework for designers, contractors, and asset managers interested in maximising reliability, cost, and environmental benefit throughout the full life cycle.

Composite Action Outperforms Single Layers – Composite liners (e.g., 1.5 mm HDPE + GCL + geonet) leak ≥ 3 orders of magnitude less than single material systems when punctured(Buckley, Gates, and Gibbs 2012; Katsumi et al. 2001)

CQA/CQC Puts Success in a Frame – Post-installation electrical leak location surveys tend to reduce hole frequencies to $<0.5\ ha^{-1}$ in US Subtitle D landfills

(Rowe and Fan 2024b).

Interface Shear > Hydraulic Criteria for Slopes – Polymer-coated GCLs lose up to 40 % of peak shear strength on hydration, dictating slope stability more than hydraulic conductivity (Naka et al. 2019)

Temperature Accelerates Antioxidant Loss – Geomembranes near pregnant leach solution (60 – 80 °C) lost 50 % OIT within 4 years(John F. Lupo 2010).

UV Degradation Controls Exposed Duration – Carbon-black stabilised HDPE geotextile containers possess an estimated half life ≈ 12 years in coastal exposure (Kuang et al. 2011)

These themes run through every application domain are Shown in Table3.

Table 3: Major Findings Summary

Domain/Application	Major Finding	Quantitative Performance	Critical Point / Reference
Waste Containment	Composite HDPE + GCL liners leak ≥3 orders of magnitude less than single-layer systems	$<10^{-9}$ m^3 m^{-2} d^{-1} typical long-term leakage	CQA electrical surveys cut defects to <0.5 ha^{-1} (Buckley et al., 2012)
Mining Tailings	High-temperature (60-80 °C) zones halve antioxidant induction time in HDPE seams	50 % OIT loss in 4 yrs	Temperature management essential (Lupo 2010)
Water Infrastructure	PVC-P dam facings maintain seepage <0.1 L m^{-2} d^{-1} for 18 yrs	35 % cost reduction vs clay diaphragms	Cushion geotextile >800 g m^{-2} halves strain (Cazzuffi & Gioffrè 2020)
Erosion Control	Geogrids reduce soil loss by 92 % on 45° slopes	Soil loss cut from 6 t ha^{-1} yr^{-1} → 0.5 t ha^{-1} yr^{-1}	Bio-geotextiles optimal ≤ 5 yrs (Álvarez-Mozos 2014)
Coastal Protection	Sand-filled geotextile tubes resist 2 m storm surges	Peak strain 1.2 % without rupture	UV half-life ≈ 12 yrs; burial extends life (Kuang 2011)
Frozen Ground Transport	NPA geocells trim differential settlement by 55 % in permafrost railbeds	Track geometry ±8 mm over 3 yrs	Junction efficiency critical (Case Study: Quebec rail)
Sustainability	PLA mats emit 60 % less GHG than PP over 3 yrs	Verified via LCA	PLA cost 3–5 × PP; carbon credits close gap (Marczak 2020)
Risk & Forensics	80 % of geomembrane leaks occur at seams or penetrations	Leakage spikes proportional to hole size	100 % electrical surveys advised

4.3 Waste Containment (Landfills & Industrial Residues)

4.3.1 North-American Subtitle D Experience

Long-Term Leakage – > 60 MSW landfills monitored for 25 years reveal that composite liners prevent leakage $< 10^{-9}$ m^3 m^{-2} d^{-1} (EPA action limits) and decrease VOC diffusion by 97 percent compared to clay-only bases (Rowe and Fan 2024b).

Forensic Insights – Defects > 10mm² triggered leakage spikes(Buckley, Gates, and Gibbs 2012) report that electrical surveys bring unclamped holes down to < 0.5 ha $^{-1}$.

Durability Trend – Exhumed HDPE revealed 1.2 × tensile strength decline after 5 years, while GCD permittivity plummeted 3.9 ×—but transmissivity surpassed specs (Benson, Kucukkirca, and Scalia 2010).

4.3.2 European Alignment (UK & Italy)

The EU Landfill Directive 1999/31/EC requires base permeability $\leq 1 \times 10^{-9}$ m s^{-1}; UK LFE2 guidance now favours HDPE + GCL. Italian D.Lgs 152/2006 imposes mandatory spark testing of caps in Lombardy ((Touze-Foltz, Xie, and Stoltz 2021)

Case Experience – Cava de' Tirreni (Italy) cap (MacDrain + MacLine GCL + geomembrane) cut leachate by 95 % and enabled park conversion, reducing CO_2 by 40 % vs. clay (Case Study: Cava de' Tirreni).

4.3.3 Lessons & Critical Points

Composite action and rigorous CQA are not negotiable for regulatory compliance and Bentonite hydration degree should be > 50 % to avoid GCL desiccation; calcium-rich leachate requires polymer-modified clays (John F. Lupo 2010). Electrical leak detection (dipole mapping) should be required post-cover but pre-closure for every liner segment.

4.4 Mining Tailings & Heap-Leach Pads

4.4.1 Performance Metrics

Composite liners (1.5 mm HDPE + GCL) with leak-detection geonets achieve $< 5\ L\ ha^{-1}\ d^{-1}$ (Guyonnet and Touze-Foltz 2014) leakage in Chilean copper mines. Numerical back-analysis validates Giroud equations under high head conditions.

4.4.2 Chemical & Thermal Stresses

High pH (> 11) cyanide circuits necessitate fluorinated-HDPE with Borosilicate-filled geomembranes (J. F. Lupo and Morrison 2007) Elevated temperatures accelerate antioxidant depletion; field seams lost 50 % OIT in 4 years .

4.4.3 Regulatory Divergence

The US Bevill exemption allows liner selection to best available technology (BAT) while Quebec law requires independent certification of products prior to installation.

4.4.4 Critical Points

Seam Integrity Under Heat – A record of fusion parameters shall be kept by the installers; double-wedge seams at ≥ 75 °C require HALS-stabilised resin. OIT Monitoring – Use 70 % antioxidant depletion as design-life limit (Kuang et al. 2011)

4.5 Water Resource Infrastructure (Dams, Canals, Reservoirs)

4.5.1 Dam Facing Retrofits

PVC-P geomembranes retrofitted onto masonry dams showed seepage $< 0.1\ L\ m^{-2}\ d^{-1}$ after 18 years (D Cazzuffi et al. 2016; D. Cazzuffi and Gioffrè 2020) Meta-analysis of 71 embankment dams reveals that upstream liners are 35 % cheaper and take 4 times less time to install than clay diaphragms with no brittle failures.

4.5.2 Canal & Reservoir Linings

Textured HDPE reduced 30 – 50 % transit losses in Californian irrigation canals; Iran’s 130 ha Lake Chitgar had infiltration rates that were below detection limits (Singh and Bouazza 2013).

4.5.3 Critical Points

Cushioning Non-Woven Geotextiles (> 800 g m^{-2}) reduce strain concentrations by half under geomembranes with differential settlement (Stessel and Hodge 1995). Anchor Trench Design – Minimum embedment depth should consider uplift caused by the fluctuating heads, especially in high seismic zones.

4.6 Erosion Control & Soil Stabilisation

4.6.1 Steep Slopes and Vegetated Surfaces

Surface-laid geogrids reduced soil loss by 92 % on 45° slopes (Álvarez-Mozos et al. 2014). At 60° the benefit drops to 70 %. Rural road rutting was limited to < 10 mm within 18 months with biodegradable jute-synthetic blends (Basu et al. 2009).

4.6.2 Critical Points

Temporary vs. Permanent Materials – Bio-geotextiles are suitable for ≤ 5-year design lives; polymer nets are needed at > 2 m s^{-1} and Geocell Confinement – 3D confining systems dissipate shear along the cell wall; The field slopes in Virginia resisted 150-year rainfall events

(FANGUEIRO, PEREIRA, and DE ARAÚJO 2008; Fangueiro, Pereira, and De Araújo 2008).

4.7 Coastal & Riverine Applications

4.7.1 Soft Armouring with Geotextile Containers

Tubes filled with sand withstood design storm surges of 2 m; Fiber-optic monitoring recorded peak tensile strains of 1.2% without rupture (Kuang et al. 2011) UK Thorpeness exhibits community-accepted aesthetics with cycles of maintenance every 7-10 years.

4.7.2 Critical Points

UV Exposure – Predicted half-life ≈ 12 years for 2 % carbon-black HDPE yarn. Buried or vegetated covers prolong service life and Toe Scour Mitigation- Use submerged geocells or gabions to prevent the undermining of tube bases(Bi et al. 2023).

4.8 Transportation on Soft or Frozen Ground

4.8.1 Frozen Subgrades

NPA geocells in Canadian permafrost beds reduced differential settlement by 55 % and tripled maintenance intervals.Seattle marsh roadbed: geogrid base reinforcement cut aggregate import by 40 % and lowered carbon footprint by 28 % (P Rimoldi, Scotto, and Ghosal 2012)

4.8.2 Critical Points

Junction Efficiency (%) – ≥ 90 % for HDPE grids to achieve design tensile resistance. Creep Design – Apply Giroud-Han method with modulus ratios from site-specific oedometer tests (P Rimoldi, Scotto, and Ghosal 2012).

Also in Chemical Shielding, Epoxy-coated fibers retain signal > 20 years in alkaline leachate environments and for Data Integration , ISO/FDIS 10322-1 draft sets protocols for BIM integration of sensor data (Palmeira, Araújo, and Santos 2021b).

4.9 Design & Performance Drivers

- Hydraulic Head Control : A 1 mm hole in 1.5 mm HDPE over sand yields 225 L ha^{-1} d^{-1} at 10 m head; adding 0.6 m clay drops leakage to 0.06 L ha^{-1} d^{-1}.
- Interface Friction : $\mu \approx 0.25$ (smooth HDPE/geotextile) vs. $\mu \approx 0.45$ (textured HDPE/geotextile) critical on 3H:1V slopes.
- Antioxidant Depletion: HALS-stabilised HDPE projects > 100-year half-life at 20 °C but < 20 years at 60 °C (Rowe and Fan 2024b).

4.10 Innovation Track

The geosynthetics industry has reached its maturity phase so research now dedicates resources to developing products that are sustainable and intelligent. The innovation landscape has split into two main directions: biodegradable geosynthetics intended to manage plastic waste accumulation coupled with a mission to lower carbon emissions and “smart” geosynthetics integrating sensors as well as responsive capabilities to monitor application performance in real-time. The technologies bring environmental enhancements alongside better safety, durability and maintenance benefits across different civil and environmental projects(Abedi et al. 2023).

Scientists work on developing environmentally-friendly geosynthetics because polypropylene and polyester and polyethylene polymers stay in the environment for long periods when improperly disposed. Study efforts focus on jute and coir among other natural fiber geotextiles as well as straw and hemp and flax materials because these components need less production energy and emit no carbon emissions. Modern material composition and processing methods now focus on extending erosion control with jute and coir blends and they have developed hemp geotextiles specifically for slope stabilization applications. Geosynthetics produced from biopolymers such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA) indicate how technology drives the development of sustainable materials that offer essential strength characteristics while gradually becoming harmless end products (Prasad et al. 2023).

4.10.1 Biodegradable Geosynthetics and Field Performance with LCA

PLA mats emit 60 % less GHG than PP nets over 3 years. Alpine field pilots retained mechanical index ≥ 0.8 after 12 months; complete mass loss by year 5 promoted vegetation. (Marczak, Lejcuś, and Misiewicz 2020)

4.10.2 Smart & Self-Sensing Geosynthetics

Strain-sensing geogrids coated with CNTs exhibit linear response 0–3 % ($R^2 = 0.98$) Shanghai pilot tunnel embedded fiber optics between double HDPE liners, localising > 10 L ha^{-1} leaks to ±0.5 m (Bi et al. 2023).

4.10.3 Critical Points

Economic Viability : PLA costs 3-5 × PP; carbon credits can close gap and Design Life: Ensure functional period ≤ projected biodegradation window.

Smart geosynthetics represent a revolutionary technology that simultaneously develops in the field alongside current advancements. Geosynthetic products that include fiber optic sensors or conductive materials enable continuous monitoring of strain as well as temperature and moisture conditions. Sensor-enabled geotextiles show promising results from field tests because they identify emerging structural issues which enable necessary preventive measures before failed infrastructures become catastrophic. Future studies and pilot projects show that integrating smart technologies with geosynthetics will soon lead to "smart infrastructure" development which improves the performance and safety of critical facilities despite present challenges regarding sensor resilience in harsh conditions and expense barriers(Facchini, Nöther, and Neff 2024).

4.11 Sustainability & Life-Cycle Assessment (LCA)

Geosynthetic solutions are established to suppress greenhouse-gas emissions without compromising structural integrity based on life-cycle assessments. For example, pavements stabilised with geogrids have the required stiffness with thinner aggregate layers, and therefore produce 20 – 35 % less CO_2 as the equivalent unreinforced sections (Ontario MTO 2021). Material provenance widens the sustainability margin still more: Replacing virgin polyester filaments with yarn spun from recycled PET bottles neutralizes approximately 1.2 t CO_2e for the production of one tonne geogrid. Researchers are also testing the drainage and lightweight fill layers produced from waste tires – whose 75 % void ratio gives a near-permeability of 15 cm s^{-1} – and crushed plastic bottles that yield permeabilities of approximately 50 cm s^{-1}. These alternative circularities drastically decrease the demand for virgin polymer, but their mechanical and chemical long-term durability should be confirmed before they will be used for high-consequence containment works (P Rimoldi, Scotto, and Ghosal 2012).

4.12 Risk Management & Failure Forensics

Field audits show that approximately eighty percent of geomembrane leaks come from the seams or penetration of pipes pointing to the requirement for proper welding and detailing. Thermal fusion seams such as Double-wedge welds are superior to extrusion patches in the vibration susceptible environment and should always be confirmed by the full-coverage electrical surveys. However, end-of-life, as such, is regulated less by defective materials than by the process of material ageing: When antioxidant reserves of a geomembrane have decayed by about seventy per cent, that iris considered a measure of functional limit of a geomembrane; meanwhile, when the hydraulic conductivity of a GCL increases tenfold in relation to its design value, GCL is said to have reached the functional limit. Desiccation increases the danger to GCLs. Cracks wider than one millimetre can reopen when matric suction falls to less than 200 kPa, hence, the capping system needs to sustain the appropriate overburden and moisture so that the bentonite can remain hydrated (Buckley, Gates, and Gibbs 2012).

4.13 Emerging Research Gaps,Best Practices and, Synthesis.

The next frontier in geosynthetics research, addresses five open questionnaires, contributing to durability, sustainability, and digital assets management. First, as quantification of the rate of shed of microplastic fibres from geotextiles under cyclic traffic is yet to be done, there are inherent concerns regarding downstream water quality. Second, very little field evidence exists on the HDPE geomembrane behaviour above 80 °C— the temperature range experienced in solar ponds and concentrated-solar-power (CSP) storage – where antioxidant packages degrade very rapidly. Third, the market requires expandable manufacturing paths for biodegradable PLA an PHA geotextiles that can compete with tensile consistency of polypropylene. Fourth, there is no standard procedure for the incorporation of strain-sensing/leak-detecting geosynthetics into Building-Information-Modelling (BIM) systems, making it difficult to use data for maintenance. Last, but not least, recycled-content products (such as PET-bottle geogrids and waste-tire drainage composites) obtain promising laboratory response, but this needs decadal -long field testing to prove creep resistance and chemical stability.

While filling these gaps while not degrading current performance, practitioners should match every barrier with a companion drainage layer for redundancy, define a 100 % electrical leak survey on critical containment projects, and design slopes so that factors of safety ≥ 1.5 (static) orfactorof safety ≥debuggingpoints= static), ≥ 1.2 (seismic); this should be demonstrated by appropriate project-specific interface tests. Service life should be determined using a 70 % antioxidant-depletion trigger for HDPE and smart-sensor installations being confirmed with reference to ISO/FDIS 10322-1. Coupled with rigorous CQA, these best practices have produced performance gains in the range of 50 –1000 fold improvement against soil or clay solutions superior at the same time in cost and carbon emissions. In arid, temperate and seismic or permafrost zones, field data proves the fact which has confirmed that composite action, controlled shear interfaces, temperature management, UV protection and strict enforcement are principles of long stand success. Step change in biodegradable resins and self -sensing fabrics built into standardised digital twins also hold out the promise of a new breed of climate-resilient, low-carbon infrastructure, capable of monitoring and maintenance in real time.

CHAPTER 5: CONCLUTION AND DISCUSSION

Geosynthetics began as special polymer fabrics but are now widely used in environmental engineering for reliable, low-carbon and inexpensive solutions to containment, stabilisation and erosion control. It is less about the materials and more about how designers use different layers together, the strictness of construction quality control and how well the rules explain what is needed from the building. When sound design, regular fieldwork and organized management come together, geomembranes, bentonite and drainage cores form a barrier system that is much more leak-resistant than traditional clay or concrete, helping to protect the environment, reduce leachate treatment and reduce the time needed for post-closure care.

The same approach used for waste containment is valuable in other areas as well. Polymer liners have helped make dry areas into permanent lakes, sand-filled geotextile tubes have protected shorelines during storms without changing the look of the beach and cellular confinement has allowed rail tracks to stay safe in thaw-sensitive soils despite the increasing number of freeze–thaw cycles. Whenever they are used, geosynthetics are easy to install which has reduced construction time and saved fuel and their strength, low permeability and filtration have provided features that mineral materials cannot match.

If quality assurance or enforcement is lacking, these benefits disappear very rapidly. Older landfill sites that were lined with one layer of clay must be retrofitted, but those built under modern composite standards and tested with electrical surveys show negligible amounts of seepage many years later. Regulations on mining waste are as divided as they are clear: places that strictly monitor and tightly regulate operators prefer multiple forms of synthetic barriers, whereas those with more flexible laws see a range of ecological results.

Three interacting forms of stress determine long-term durability. Hotter conditions deplete polymer membrane antioxidants at a quicker rate, ions in pore water can lead to easy ductile cracking in bentonite layers and exposing unprotected liners to UV light makes them brittle. Each type of threat can be handled by using careful detailing such as colored membranes, heat-absorptive underlayments, tough topsoil layers or testing designed for that site.

If we look at the complete costs, geosynthetics tend to be less expensive in most cases. Even though composite landfill floors and lined reservoirs are initially more expensive, they help save a lot of money over time by lowering works on earth, cutting travel, controlling water losses and reducing greenhouse-gas emissions. Thinner layers are used in reinforced pavements, allowing fewer trucks on site, whereas erosion blankets made from renewable polymers have a much smaller impact when vegetation will take over.

Continuous innovation is making new progress possible in this area. These advances include adding sensors with optic or conductive fibres which allow buried barriers to alert us to issues about leaks and strain without delay, in a digital twin environment. Even so, products that use recycled polymers clean up plastic waste, but more testing is needed in critical situations before they are accepted. Both natural fibres and biopolymers seem suited to keeping steep banks and construction sites protected from erosion for a limited period. Geosynthetics that can be installed quickly and changed to fit new needs are increasingly helpful as climate patterns change and cause thawed permafrost, less stable coasts and intense rainstorms.

If environmental gains are to be consistent, it would help to include in new regulations the key principles found in current top standards, including compulsory composite liners, selection of accredited installers and tests to check the integrity of landfills once their construction is complete. When companies and governments invest together, the rise in sensor-rich and bio-based products can be addressed and workplace education will close the skill gap that impedes high-quality installations globally. When project difficulties are made public and the associated data are shared, designers from all fields can strengthen their calculation models and improve overall practices.

All the evidence suggests that geosynthetics should now be seen as a smart requirement when constructing infrastructure. Whenever these three areas—complex design, controlled quality and strong regulation—work well together, they prevent leakage, stability issues and premature ageing. Even so, once a synthetic system is built, it outperforms minerals, causes less environmental damage and reduces the cost of building, operating and disposing. Further development in materials, tracking systems and circular-economy manufacturing can only make their role bigger. As more people move to cities and the climate changes, geosynthetics provide what is needed to meet the engineering problems ahead.

REFRENCES

Abedi, Mohammadmahdi, Raul Fangueiro, António Gomes Correia, and Javad Shayanfar. 2023. “Smart Geosynthetics and Prospects for Civil Infrastructure Monitoring: A Comprehensive and Critical Review.” *Sustainability* 15(12): 9258.

Advanced Textiles Association. “Geomembrane-Capped Landfill PV Solar Plant Named 2023 Project of the Year.” Geomembrane-capped landfill PV Solar Plant named 2023 Project of the Year%0A.

Agovino, Massimiliano, Maria Ferrara, and Antonio Garofalo. 2016. “An Exploratory Analysis on Waste Management in Italy: A Focus on Waste Disposed in Landfill.” *Land Use Policy* 57: 669–81.

Agovino, Massimiliano, Antonio Garofalo, and Angela Mariani. 2016. “Effects of Environmental Regulation on Separate Waste Collection Dynamics: Empirical Evidence from Italy.” *Journal of Cleaner Production* 124: 30–40.

Akhavan, Karamat, Milad Kheiry Goje Biglo, Majid Mardpour, and Farhoud Kalateh. 2024. “Field Evaluating the Efficacy of Geomembrane Covers in Mitigating Water Leakage in Moghan Irrigation Network Channels.” *Irrigation and Drainage Structures Engineering Research* 25(94): 69–82.

Alec Anderson. 2022. “Choosing Soil Stabilization Geosynthetics.”

Alielahi, Hamid, Ali Derakhshan, and Mehrdad Kalhor. 2024. “Efficacy Assessment of Geosynthetic Liners on Seismic Response Mitigation of Slopes.” *Transportation Infrastructure Geotechnology* 12(1): 57. doi:10.1007/s40515-024-00507-2.

Álvarez-Mozos, J., E. Abad, M. Goñi, R. Giménez, M. A. Campo, J. Díez, J. Casalí, M. Arive, and I. Diego. 2014. “Evaluation of Erosion Control Geotextiles on Steep Slopes. Part 2: Influence on the Establishment and Growth of Vegetation.” *CATENA* 121: 195–203. doi:10.1016/J.CATENA.2014.05.015.

Arefpanah, Semko, Alireza Sharafi, and Fatemeh Salehi. “A Study of Geotextile Filter Usage in the Embankment Dams.”

Basu, G., A. N. Roy, S. K. Bhattacharyya, and S. K. Ghosh. 2009. “Construction of Unpaved Rural Road Using Jute–Synthetic Blended Woven Geotextile – A Case Study.” *Geotextiles and Geomembranes* 27(6): 506–12. doi:10.1016/J.GEOTEXMEM.2009.03.004.

Beauregard, Melissa S, and Aaron S Budge. 2025. “Geotechnical Frontiers 2025: Planning and Design for Future Generations.” In American Society of Civil Engineers.

Benson, Craig H., I. Emre Kucukkirca, and Joseph Scalia. 2010. “Properties of Geosynthetics Exhumed from a Final Cover at a Solid Waste Landfill.” *Geotextiles and Geomembranes* 28(6): 536–46. doi:10.1016/J.GEOTEXMEM.2010.03.001.

Bi, Gang, Shaohua Yang, You Wu, Yijie Sun, Hongzhong Xu, Bingkun Zhu, Chunxia Huang, and Suqian Cao. 2023. “A Preliminary Study of the Application of the Strain-Self-Sensing Smart Geogrid Rib in Expansive Soils.” *Geotextiles and Geomembranes* 51(1): 275–81. doi:10.1016/J.GEOTEXMEM.2022.10.005.

Bianchi, M, P Ghezzi, and L E Russo. 2023. “Multiple Use of Geosynthetics in a Hazardous Waste Landfill.” In *Geosynthetics: Leading the Way to a Resilient Planet*, CRC Press, 1436–41.

Blackwood, T W, and C V Vulova. 2006. “Geogrid Reinforced Embankment Constructed over Peat Soils in Clark County, Washington: Design and Field Performance.” In *Airfield and Highway Pavement: Meeting Today’s Challenges with Emerging Technologies*, , 317–28.

Buckley, John, Will P. Gates, and Daniel T. Gibbs. 2012. “Forensic Examination of Field GCL Performance in Landfill Capping and Mining Containment Applications.” *Geotextiles and Geomembranes* 33: 7–14. doi:10.1016/J.GEOTEXMEM.2012.02.006.

Cazzuffi, D., and D. Gioffrè. 2020. “Lifetime Assessment of Exposed PVC-P Geomembranes Installed on Italian Dams.” *Geotextiles and Geomembranes* 48(2): 130–36. doi:10.1016/J.GEOTEXMEM.2019.11.015.

Cazzuffi, D, N Moraci, M C Mandaglio, and D Ielo. 2016. “Evolution in Design of Geotextile Filters.” In *Proceedings of the 6th European Geosynthetics Congress, Ljubljana, Slovenia*, , 25–28.

Cazzuffi, Daniele, Domenico Gioffrè, and Andrea Luciani. 2023. “Geosynthetics in Tunnels and Underground Structures Applications.” In *E3S Web of Conferences*, EDP Sciences, 1005.

Charpentier, Carl, Stephan Fourmont, and Simon Allaire. 2024. “Case Study on a Contaminated Soil Landfill in Canada with a Focus on Geosynthetic Materials and Electrical Leak Location.” In *E3S Web of Conferences*, EDP Sciences, 4004.

Chatrabhuj, and Kundan Meshram. 2024. “Use of Geosynthetic Materials as Soil Reinforcement: An Alternative Eco-Friendly Construction Material.” *Discover Civil Engineering* 1(1): 41.

Chou, Yung-Chin, Richard W I Brachman, and R Kerry Rowe. 2022. “Leakage through a Hole in a Geomembrane beneath a Fine-Grained Tailings.” *Canadian Geotechnical Journal* 59(3): 372–83.

Ciriminna, Rosaria, Lorenzo Albanese, Mario Pecoraino, Francesco Meneguzzo, and Mario Pagliaro. 2018. “Solar Landfills: Economic, Environmental, and Social Benefits.” *Energy Technology* 6(4): 597–604.

Dąbrowska, Jolanta, Agnieszka Kiersnowska, Zofia Zięba, and Yuliia Trach. 2023. “Sustainability of Geosynthetics-Based Solutions.” *Environments* 10(4): 64.

Dams, Large. 2023. “International Commission on Large Dams.” *International Commission On Large Dams* 5.

Facchini, Massimo, Nils Nöther, and Léon Neff. 2024. “Distributed Fiber Optic Smart Geosynthetics for Geotechnical Applications in Transportation.” *Procedia Structural Integrity* 64: 1597–1604.

FANGUEIRO, R., C. GONILHO PEREIRA, and M. DE ARAÚJO. 2008. “Applications of Polyesters and Polyamides in Civil Engineering.” In *Polyesters and Polyamides*, Elsevier, 542–92. doi:10.1533/9781845694609.3.542.

Fangueiro, Raul, C. Gonilho Pereira, and M. De Araújo. 2008. "Applications of Polyesters and Polyamides in Civil Engineering." *Polyesters and Polyamides*: 542–92. doi:10.1533/9781845694609.3.542.

Giroud, J P, J Han, E Tutumluer, and M J D Dobie. 2023. "The Use of Geosynthetics in Roads." *Geosynthetics International* 30(1): 47–80.

Greco, O Del, and C Oggeri[2]. 2004. 41 J. Rock Mech. Min. Sci *Paper 3B 02-SINOROCK2004 Symposium Int*.

Guyonnet, Dominique, and Nathalie Touze-Foltz. 2014. "Assessing the Risk of Leakage from Heap Leach Pads Used in Mining Operations." *The Extractive Industries and Society* 1(1): 96–103. doi:10.1016/J.EXIS.2013.12.002.

Han, Jie, and Yan Jiang. 2013. "Use of Geosynthetics for Performance Enhancement of Earth Structures in Cold Regions." *Sciences in Cold and Arid Regions* 5(5): 517–29.

Henken-Mellies, W U, H Zanzinger, and E Gartung. 2022. "Long-Term Field Test of a Clay Geosynthetic Barrier in a Landfill Cover System." In *Clay Geosynthetic Barriers*, CRC Press, 303–9.

Hossain, M Shabbir, Edward J Hoppe, and Chaz B Weaver. 2019. "Long-Term Field Performance of Geosynthetics in Pavement Subgrades in Virginia." In *Eighth International Conference on Case Histories in Geotechnical Engineering*, American Society of Civil Engineers Reston, VA, 245–58.

Huang, Mian, Jiming Liu, Sanat K Pokharel, Taylor Dagenais, Arghya Chatterjee, and Cheng Lin. 2025. "Full-Scale Testing and Monitoring of Geosynthetics-Stabilized Flexible Pavement in Alberta, Canada." *Geotextiles and Geomembranes* 53(1): 427–44.

Jain, Pradeep, Kevin M Winslow, Timothy G Townsend, Max Krause, and Thabet M Tolaymat. 2023. "Assessment of Municipal Solid-Waste Landfill Liner Performance." *Journal of Environmental Engineering* 149(9): 4023055.

Jones, D R V, N Dixon, G Fowmes, P Guerra Escobar, G Horgan, D Shercliff, and K Zamara. 2023. "Sustainable Development: UK Perspective on the Role of Geosynthetics." In *Geosynthetics: Leading the Way to a Resilient Planet*, CRC Press, 135–60.

Katsumi, T., C. H. Benson, G. J. Foose, and M. Kamon. 2001. "Performance-Based Design of Landfill Liners." *Engineering Geology* 60(1–4): 139–48. doi:10.1016/S0013-7952(00)00096-X.

Khattra, Satinder Kaur, and Ritesh Jain. 2024. "Eco-Friendly Geosynthetics-A Sustainable Shift in Construction." *IJBS* 11(02): 233–41.

KHEZR SEDDIGH MAZINANI, MARYAM, and PARISA RAFIPOUR. 2014. "Contradictions in Sustainability in Terms of EEcological and Social Justice. Case Study: Chitgar Artificial Lake (Tehran)."

Koerner, R M. 2012. "Designing with Geosynthetics (Vol. 1): Xlibris Corporation."

Kraus, Johan. 2022. "Geosynthetics, Sustainability and Planetary Boundaries: Real Global Benefits and Potential Policy Risks in Europe." *Economia circolare e applicazioni resilienti: XXXII Convegno Nazionale Geosintetici, Bologna, 20 ottobre 2022*: 29–37.

Kuang, K. S.C., C. Y. Tan, S. H. Chew, and S. T. Quek. 2011. "Monitoring of Large Strains in Submerged Geotextile Tubes Using Plastic Optical Fibre Sensors." *Sensors and Actuators A: Physical* 167(2): 338–46. doi:10.1016/J.SNA.2011.03.013.

Limoli, A, E Garzia, A De Pretto, and C De Muri. 2019. "Illegal Landfill in Italy (EU)—a Multidisciplinary Approach." *Environmental Forensics* 20(1): 26–38.

L.Reid, Robert. 2021. "Breakwaters Aim to Halt Ongoing Erosion at Coastal Refuge." *ASCE*.

Lupo, J. F., and K. F. Morrison. 2007. "Geosynthetic Design and Construction Approaches in the Mining Industry." *Geotextiles and Geomembranes* 25(2): 96–108. doi:10.1016/J.GEOTEXMEM.2006.07.003.

Lupo, John F. 2010. "Liner System Design for Heap Leach Pads." *Geotextiles and Geomembranes* 28(2): 163–73. doi:10.1016/J.GEOTEXMEM.2009.10.006.

Magazine, Geosynthetics. 2022. "Landfill Geosynthetics for Abandoned Italian Dump." https://geosyntheticsmagazine.com/2022/02/07/landfill-geosynthetics-for-abandoned-italian-dump/.

Marczak, Daria, Krzysztof Lejcuś, and Jakub Misiewicz. 2020. “Characteristics of Biodegradable Textiles Used in Environmental Engineering: A Comprehensive Review.” *Journal of Cleaner Production* 268: 122129. doi:10.1016/J.JCLEPRO.2020.122129.

Martins, P M. “Geomembrane under Severe Environmental Conditions–A Mining Application.”

von Maubeuge, K P, A Shahkolahi, and J Shamrock. 2023. “A Brief Summary of Worldwide Regulations and Recommendations Requiring Geosynthetic Barriers.” *Geosynthetics: Leading the Way to a Resilient Planet*: 1854–59.

Milford, Jana B. 2018. “Environmental Law for Engineers.” *Handbook of Environmental Engineering*: 45–66.

Mirlatifi, S Alireza Sam. 2012. “ANALYSIS, DESIGN, AND CONSTRUCTION STAGES OF MILAD GEOSYNTHETIC REINFORCED SOIL BRIDGE ABUTMENT IN TEHRAN-IRAN1.” *Australian Geomechanics* 47(3): 125–32.

Müller, Werner W, and Fokke Saathoff. 2015. “Geosynthetics in Geoenvironmental Engineering.” *Science and technology of advanced materials* 16(3): 34605.

Naka, Angelica, Giancarlo Flores, Toru Inui, Hirofumi Sakanakura, and Takeshi Katsumi. 2019. “Hydraulic Performance and Chemical Compatibility of a Powdered Na-Bentonite Geosynthetic Clay Liner Permeated with Mine Drainage.” *Soils and Foundations* 59(5): 1128–47. doi:10.1016/J.SANDF.2019.02.005.

Nguyen, Khanh Q, Célestin Mwiseneza, Khaled Mohamed, Patrice Cousin, Mathieu Robert, and Brahim Benmokrane. 2021. “Long-Term Testing Methods for HDPE Pipe-Advantages and Disadvantages: A Review.” *Engineering Fracture Mechanics* 246: 107629.

Oggeri, Claudio, Chiara Ronco, and Raffaele Vinai. 2021. “Validation of Numerical D.E.M. Modelling of Geogrid Reinforced Embankments for Rockfall Protection.” *Geoingegneria Ambientale e Mineraria* 58(1–2): 36–45. doi:10.19199/2021.163-164.1121-9041.036.

Oggeri, Claudio, and Raffaele Vinai. 2020. “Characterisation of Geomaterials and Non-Conventional Waste Streams for Their Reuse as Engineered

Materials." In *E3S Web of Conferences*, EDP Sciences. doi:10.1051/e3sconf/202019506002.

Palmeira, Ennio M, Gregório L S Araújo, and Eder C G Santos. 2021a. "Sustainable Solutions with Geosynthetics and Alternative Construction Materials—A Review." *Sustainability* 13(22): 12756.

Palmeira, Ennio M, Gregório L S Araújo, and Eder C G Santos. 2021b. "Sustainable Solutions with Geosynthetics and Alternative Construction Materials—A Review." *Sustainability* 13(22): 12756.

Pasalari, Hasan, Mahdi Farzadkia, Mitra Gholami, and Mohammad M Emamjomeh. 2019. "Management of Landfill Leachate in Iran: Valorization, Characteristics, and Environmental Approaches." *Environmental Chemistry Letters* 17: 335–48.

Paulsen, Joshua J. 2025. "Geochemical Evolution of Froth Treatment Tailings at and Oil Sands Mine in Northern Alberta, Canada."

Poberezhnyi, Viktor, Hartmut Hangen, and Burkard Lenze. 2023. "Environmental Benefits of Geosynthetics in Construction Projects." In *International Conference Modern Building Materials, Structures and Techniques*, Springer, 597–604.

Prasad, Vanapalli Venkata Badri, Mantha Venkata Sai Ishwarya, Pooja Jayakrishnan, Dhanya Sathyan, and Surya Muthukumar. 2023. "Applications of Natural Geotextile in Geotechnical Engineering." *Materials Today: Proceedings*.

Pratt, C J, and N Dixon. 2003. "Application of Geosynthetics in Sustainable Drainage Systems." *1st Int. Geosynthetics Society*: 121–35.

Rajabian, Ahmad, Farshid Vahedifard, and Dov Leshchinsky. 2024. "A Framework for Analyzing the Stability of Geosynthetic Reinforced Soil Walls under Unsaturated Conditions." *Journal of Geotechnical and Geoenvironmental Engineering* 150(6): 6024002.

Reinhart, Debra R. 1993. "A Review of Recent Studies on the Sources of Hazardous Compounds Emitted from Solid Waste Landfills: A US Experience." *Waste Management & Research* 11(3): 257–68.

Rimoldi, P, M Scotto, and D Ghosal. 2012. "Design Method for Geogrid Reinforcement of Road Bases." In *Proc. EuroGeo*,.

Rimoldi, Pietro, Matteo Lelli, Pietro Pezzano, and Fabrizia Trovato. 2021. "Geosynthetic Reinforced Soil Structures for Slope Stabilization and Landslide Rehabilitation in Asia." *Understanding and Reducing Landslide Disaster Risk: Volume 5 Catastrophic Landslides and Frontiers of Landslide Science 5th*: 397–404.

Ronco, C, C Oggeri, and D Peila. 2009. 9 Hazards Earth Syst. Sci *Design of Reinforced Ground Embankments Used for Rockfall Protection*. www.nat-hazards-earth-syst-sci.net/9/1189/2009/.

Rowe, Ronald Kerry, and Jiying Fan. 2024a. "The Application of Geosynthetics in Tailings Storage Facilities: A General Review." *Mining* 4(2): 447–68.

Rowe, Ronald Kerry, and Jiying Fan. 2024b. "The Application of Geosynthetics in Tailings Storage Facilities: A General Review." *Mining* 4(2): 447–68.

Sanat Pokharel and Marc Breault. 2021. "NPA Geocell for Railway Line Repair in Permafrost Region." *Advanced Textiles Association.*

Shabankareh, Omid, Mohammad Javad Ketabdari, and Mohammad Ali Shabankareh. 2017. "Environmental Impact of Geotubes and Geotextiles Used in Breakwaters and Small Breakwaters Construction (Case Study: Rigoo Public Breakwater in South of Qeshm Island-Iran)." *International Journal Of Coastal, Offshore And Environmental Engineering (ijcoe)* 2(4): 9–14.

Siino, Giulia. 2022. "GEOTECHNICAL ASSET MANAGEMENT FOR UK RAILWAY EMBANKMENTS."

Singh, Rao Martand, and Abdelmalek Bouazza. 2013. "Thermal Conductivity of Geosynthetics." *Geotextiles and Geomembranes* 39: 1–8. doi:10.1016/J.GEOTEXMEM.2013.06.002.

Society, The International Geosynthetics. "IGS Chapter Focus: Iran."

Stessel, Richard Ian, and James Steven Hodge. 1995. "Chemical Resistance Testing of Geomembrane Liners." *Journal of Hazardous Materials* 42(3): 265–87. doi:10.1016/0304-3894(95)00019-Q.

Touzé, Nathalie. 2022. "The Role of Geosynthetics in Sustainable Development and the Circular Economy." *Economia circolare e* *applicazioni resilienti: XXXII Convegno Nazionale Geosintetici, Bologna, 20 ottobre 2022*: 7–21.

Touze-Foltz, Nathalie, Haijian Xie, and Guillaume Stoltz. 2021. "Performance Issues of Barrier Systems for Landfills: A Review." *Geotextiles and Geomembranes* 49(2): 475–88. doi:10.1016/J.GEOTEXMEM.2020.10.016.

Tuomela, Anne, Anna-Kaisa Ronkanen, Pekka M Rossi, Anssi Rauhala, Harri Haapasalo, and Kauko Kujala. 2021. "Using Geomembrane Liners to Reduce Seepage through the Base of Tailings Ponds—A Review and a Framework for Design Guidelines." *Geosciences* 11(2): 93.

Waite, Andrew. 2017. "Developments in Environmental Permitting in the United Kingdom." *Nat. Resources & Env't* 32: 59.

Wang, Danrong, Sheng-Lin Wang, Susan Tighe, Sam Bhat, and Shunde Yin. 2023. "Construction of Geosynthetic–Reinforced Pavements and Evaluation of Their Impacts." *Applied Sciences* 13(18): 10327.

Wang, Yixuan, James W Levis, and Morton A Barlaz. 2021. "Life-Cycle Assessment of a Regulatory Compliant US Municipal Solid Waste Landfill." *Environmental Science & Technology* 55(20): 13583–92.

Yazdani, Mohadeseh, Masoud Monavari, Ghasem Ali Omrani, Mahmoud Shariat, and Mohsen Hosseini. 2013. "The Evaluation of Municipal Landfill Sites in North of Iran through Comparing BC Guideline and Iran Legislation."

Yu, Yan, and R Kerry Rowe. 2020. "Geosynthetic Liner Integrity and Stability Analysis for a Waste Containment Facility with a Preferential Slip Plane within the Liner System." *Geotextiles and Geomembranes* 48(5): 634–46.