Soils and Rocks

An International Journal of Geotechnical and Geoenvironmental Engineering

www.soilsandrocks.com

ISSN 1980-9743
ISSN-e 2675-5475

The hydraulic conductivity of fuel permeated geosynthetic clay liners: a bibliometric study

Julia Favretto[1#], Adeli Beatriz Braun[1], Márcio Felipe Floss[2], Pedro Domingos Marques Prietto[1]

Review Article

Keywords
Soil contamination
Hydraulic barriers
Bentonite geocomposites
Database
Bibliometric indicators

Abstract

The use of geosynthetic clay liners (GCLs) as a hydraulic barrier for contaminants containment has proved to be an efficient alternative for the soil and groundwater protection. This geocomposite can be used in engineering systems to contain accidental spills and leaks of fuel in distribution centers, reservoirs and resulting from transport, where the geosynthetic acts as a protection against subsoil contamination. However, there is a concern about the behavior of GCLs in the face of these contaminants about possible changes in their properties, in order to compromise the retention capacity and permeability of the material. In this regard, the present work aimed to carry out a systemic and bibliometric study of publications related to the hydraulic conductivity of GCLs after contact with some type of fuel, available in the Scopus database (Elsevier) and Web of Science (Clarivate). The primary data selected directly from the databases were analyzed, making it possible to filter the publications that made up the bibliographic portfolio of the research, resulting in 14 selected documents, which were synthesized, and the main points were highlighted. From the bibliographic portfolio, bibliometric indexes of scientific production were created, as well as the temporal distribution of publications, authors, countries, and scientific journals that most contribute to the theme and the terms most evidenced in the documents. The panorama observed through bibliometrics was that it is a very recent theme, which still has a lack of scientific production, revealing itself as a promising area for the development of research.

1. Introduction

Environmental protection in infrastructure facilities has been receiving greater concern over time with respect to the main problems such as the intrusion of toxic contaminants in the subsurface soil and groundwater. The low hydraulic conductivity of bentonite geocomposites encouraged its use in several civil engineering to flow containment applications, such as hydraulic barriers in waste disposal, landfill bottom and cover systems, ponds, canals, reservoirs, whose first associated function was to control the water percolation (Petrov et al., 1997; Viana et al., 2011).

Geocomposites of bentonite or geosynthetic clay liners (GCLs) are industrialized products, consisting of a bentonite layer chemically or mechanically bonded to geotextiles and/or geomembranes (Lake & Rowe, 2000; Bouazza, 2002; Bouazza & Vangpaisal, 2007). The low permeability of GCLs is due to the high swelling capacity of the bentonite present in the compound.

Effective barriers against the advective transport of both liquids and gases can be achieved with the use of GCLs. In the absence of any other materials, the permeant flow is controlled by the permeability of the GCL with respect to that fluid (Rowe, 2020). The hydraulic conductivity k of GCLs is normally in the range of (1 to 5) x 10^{-11} m/s when permeated with water (Koerner, 2012). Bouazza (2002) presents compiled results from various sources of laboratory tests conducted on GCLs, that indicate values of hydraulic conductivity with respect to water varying between 2 x 10^{-12} m/s and 2 x 10^{-10} m/s, depending on applied confining stress.

The GCLs can also be used in secondary containment barriers for chemicals, as part of a composite containment system in applications to contain accidental fuel spills, caused by leaks in underground reservoirs, spills and accidents during the exploration, refinement, transport, and storage operations of oil and its derivatives, in order to provide short-term barrier to prevent site contamination (Rowe et al., 2004; Mukunoki et al., 2005; Rowe et al., 2006; Rowe et al., 2008; Hosney & Rowe, 2014; McWatters et al., 2016; McWatters et al., 2020).

[#]Corresponding author. E-mail address: juliafavretto@hotmail.com
[1]Universidade de Passo Fundo, Passo Fundo, RS, Brasil.
[2]Instituto de Ciências Agronômicas, Passo Fundo, RS, Brasil.

Submitted on November 23, 2022; Final Acceptance on April 18, 2023; Discussion open until November 30, 2023.
https://doi.org/10.28927/SR.2023.012222

When GCLs is applied to contain liquids other than water, its hydraulic performance can potentially be affected in some cases due to the chemistry of the permeant fluid and bentonite. To ensure good performance of the GCLs as a barrier, the compatibility between the bentonite and the expected pollutant liquid should be verified (Mazzieri et al., 2000) and it is necessary sufficient hydration of the bentonite with water before contact with contaminants (Mazzieri et al., 2000; Rowe et al., 2005a; Rowe et al., 2005b; Rowe et al., 2007).

Research on the performance of GCLs has made considerable progress in recent decades (e.g., Hewitt & Daniel, 1997; LaGatta et al., 1997; Bouazza, 2002; Bouazza et al., 2006; Touze-Foltz et al., 2006; Meer & Benson, 2007; Rowe, 2012; Bradshaw & Benson, 2013; Rowe, 2014; Rowe et al., 2016; Bouazza et al., 2017; Rowe et al., 2019; Wang et al., 2019; Carnero-Guzman et al., 2021; Rowe & AbdelRazek, 2021). However, to-date there has been very little research relating to the use of GCLs in fuel containment barriers, as already noted by Rowe et al. (2008) years ago with respect to GCLs in contact with hydrocarbons.

This study employs a quantitative-descriptive bibliometric approach to locate and analyze existing studies on the use of GCLs in fuel containment barriers and their interaction with contaminants, with a focus on changes in permeability and hydraulic conductivity. Two of the most widely used databases in the field are Scopus and the Web of Science (WoS). Scopus is the largest database of abstracts and citations of literature, scientific journals, books, and peer-reviewed scholarly works. The Web of Science (WoS), on the other hand, is a bibliographic reference database that contains information about scientific production from 1945 onwards (Scopus, 2022; Web of Science, 2022).

Bibliometrics is a tool that expands knowledge on the subject presented and is characterized by a search with pre-defined criteria, minimizing implicit tendencies of the researcher and enabling the direction of new research with greater precision (Macedo et al., 2010). This type of research, in addition to allowing the collection of data from primary sources, also allows the collection of secondary data through the elaboration of a bibliographic portfolio, which represents the perception and delimitation of the authors regarding the relevance and representativeness of the studies according to with the interests of the research and the topic addressed (Braun et al., 2019).

The objective of this article is to address a significant research gap related to the hydraulic conductivity of geosynthetic clay liners after exposure to fuel. Through a thematic synthesis of the main studies in this area and an examination of publication patterns (including temporal distribution, authors, countries, and scientific journals that contribute most to the topic) it is expected to identify gaps in the literature and provide guidance for future research.

2. Materials and methods

The methodology of this study involved a systematic and bibliometric research using qualitative and quantitative approaches, which was based on the studies of Braun et al. (2019) and Visentin et al. (2020).

2.1 Database and research delimitation

This research was conducted using two prominent scientific databases, Scopus (Elsevier) and Web of Science (Clarivate), selected for their extensive coverage of scientific publications and their ability to provide reliable citation data. No restrictions were placed on the types of documents, type of access and areas of knowledge that publish on the subject. Therefore, this review encompasses a broad range of materials, including scientific articles, reviews, books and book chapters, conference proceedings, contributions to edited volumes and working papers.

The analysis time considered in the research was until the year 2022, when the last query in the databases was performed. The initial year of the research was not specified, to verify the entire scientific contribution related to the topic. The language selected for research in both databases was English. In Scopus, the search was carried out using as a criterion that the combinations of the selected keywords were found in the "title, abstract and keywords" of the publications. In WoS, the keyword search criterion was in the "topic" of the publications, which corresponds to the "title, abstract, author's keywords and keywords plus", the latter consisting of words or phrases created or extracted from the titles of cited articles and retrieved by searching the topic field.

2.2 Selection and composition of the bibliographic portfolio

Initially, the keywords for the research were defined, being: "hydraulic conductivity", "permeability", "GCL", "geosynthetic clay liners", "fuel", "oil", "petroleum", "hydrocarbons", "diesel", "biodiesel", "gasoline" and "ethanol".

For the combination of words, the Boolean operators "AND" and "OR" were used. The use of the AND operator is necessary when you want all the terms used to appear in publications, while the OR operator indicates that at least one of the terms must appear in the document. In the case of a term or expression, operators (" ") were also used in order to represent a single word in the search.

The systemic search of primary data (raw) in both databases, Scopus and WoS, considering the previously defined boundaries, included 54 documents, 34 of which were found in the Scopus database and 20 in the WoS. These publications were stored in the Bibliometrix/R software, which allows for the initial filtering of the publications; assists in coding and managing data and ideas, visually modeling and generating reports through Biblioshiny, a web interface to Bibliometrix, which facilitates data analysis; and allows extracting the main information from each publication.

The filtering process used in this study consisted of reading the entire text of each publication. First, duplicate publications (14 in total) were excluded, followed by those that were unavailable for full download (3 in total, indexed in Scopus). Additionally, 15 publications were excluded due to their incompatibility with the study theme, indexed in Scopus, and 6 more were excluded from WoS. Finally, 2 publications that were redundant and incompatible with the study theme, indexed in both databases, were also excluded. Thus, a total of 40 publications were excluded, and the bibliographic portfolio was reduced to 14 publications, which correspond to specific works on the hydraulic conductivity of GCLs permeated with some type of combustible fluid. Figure 1 presents the synthesis of the process of treatment of the primary results for the construction of the work portfolio.

When comparing the initial results of the research, there is a greater difference in the number of publications indexed in each database. However, after a more careful analysis, it is seen that this difference significantly reduces the composition of the portfolio, so that the difference of articles exclusively indexed is reduced to only 2 articles, which are indexed in Scopus, against none exclusively indexed in WoS. The other articles that make up the group are found in both databases.

In the end, 14 articles were part of the set of publications related to the theme, also called the bibliographic research portfolio (Petrov et al., 1997; Mazzieri et al., 2000; Rowe et al., 2004; Mukunoki et al., 2005; Rowe et al., 2005a; Rowe et al., 2005b; Rowe et al., 2006; Rowe et al., 2007; Rowe et al., 2008; Sari & Chai, 2013; Hosney & Rowe, 2014; Gitipour et al., 2015; McWatters et al., 2016; McWatters et al., 2020).

With the portfolio defined, the analysis of the selected works began and the elaboration of indicators, such as number of publications per year, authors, countries and journals that contribute most with publications on this topic. And finally, each article was analyzed individually, and comparisons were made to detect higher order themes within the literature and thus compose a synthesis regarding the theme.

3. Analysis and results

3.1 Temporal distribution of scientific production of primary data

The distribution referring to the temporal cut of the data of the first phase of the research, where 54 publications were found (34 in Scopus and 20 in WoS), is represented in Figure 2. The temporal distribution of the works found is situated in a period of 24 years, starting in 1997 until 2021.

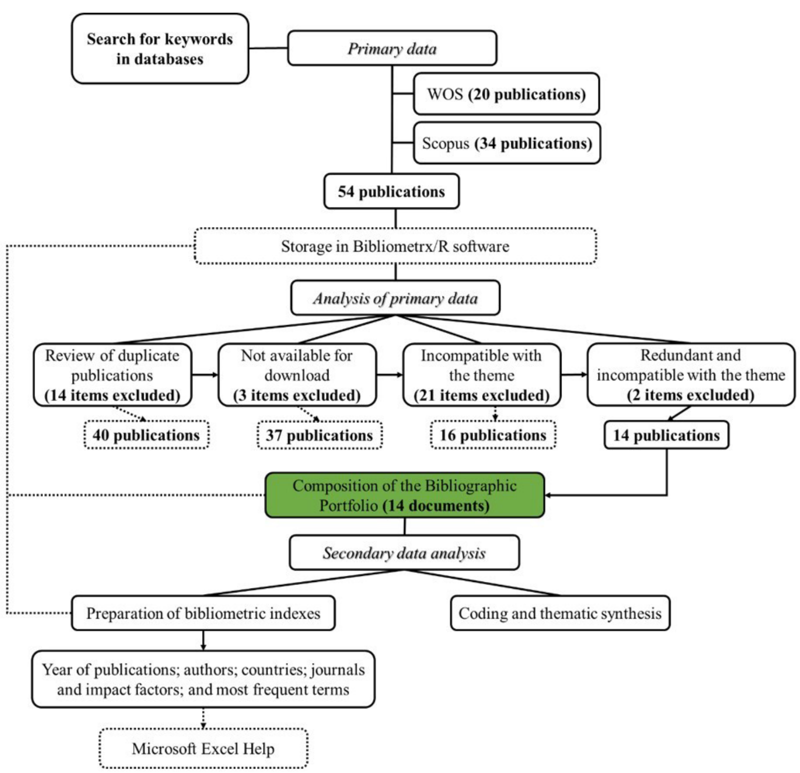

Figure 1. Scheme of the bibliographic portfolio construction process.

It was observed that the first research on the subject began in mid-1997. However, clearly in the following years there were no publications, and these were resumed with greater frequency only from 2004 onwards. There was no gradual growth, there were always oscillations in the number of annual publications, with the peak being reached in 2016, and the last publication in 2021.

3.2 Temporal distribution of scientific production of secondary data

This item presents the evolution of scientific production only of publications related to the subject of study, which make up the bibliographic portfolio (14 articles) and from which subsequent analyses are presented. The temporal distribution of these works is situated in a period of 12 years, as can be seen in Figure 3.

The more specific theme was already present in the first publications by Petrov et al. (1997). However, from this first publication there were no major developments, since the number of annual publications and the accumulated frequency remained constant, except for the year 2005, which peaked in publications directly related to the theme. Another important finding is related to the last publication specific to the theme that occurred in 2020 by McWatters et al. (2020), approximately two years from the date of this research, which shows that studies are evolving quite slowly, with extended periods without publication.

Therefore, the scientific production related to the evaluation of the hydraulic conductivity of the GCL material when in contact with fuels still lacks research, seen by the low number of publications over the years. In view of this and the fact that it is a very recent theme, the scenario, in addition to being relevant, is promising for the development of new works in this area.

3.3 Authors with the greatest contribution to the topic

Based on the 14 selected publications, it was possible to identify the authors with more publications on the subject. In total, 33 different authors were responsible for the publications, and of these, 10 authors have two or more publications.

Highlight is given to researcher Ronald Kerry Rowe, professor and researcher at Queen's University, (Kingston, Canada), which has the largest number of published research in the area and is one of the leaders in research on GCL. Rowe is a renowned researcher in geoenvironmental engineering, considered one of the pioneers in research on waste barrier systems. In a broad search in Scopus databases, searching documents where only the words "GCL" or "geosynthetic clay liners" appear in the title, abstract or keywords, Rowe appears first in terms of the number of publications, with a total of 98 articles, distributed in the period from 1997 to 2021. The same search, when performed in the WoS database searching for "topic", resulted in a total of 110 articles, distributed in the period from 1997 to 2021.

Of the 14 analyzed works that made up the bibliographic portfolio, Rowe contributed in 11 works, which represents 79% of the portfolio. In second place is Toshifumi Mukunoki with participation in 7 published articles, equivalent to 50% of the total, followed by Richard J. Bathurst with 6 articles, 43% of the total and by Paul Hurst, who collaborated in 4 articles, 29% of the total. Six authors participated in 2 publications, each representing 14.3% of the total. The other authors (23 remaining) contributed to only 1 publication, or 7.14% of the total.

In Figure 4, generated by the Biblioshiny interface of the Bibliometrix/R software, it is possible to better observe the distribution networks of publications among the 10 main authors highlighted. The authors are divided into two large groups that publish on the subject, with Rowe as the highlight. The greater the thickness of the branch, the greater the number of publications together between the authors. The largest collaboration network is between Rowe, Bathurst, Mukunoki and Hansen. Group 1 can be considered as the main research group on the topic addressed.

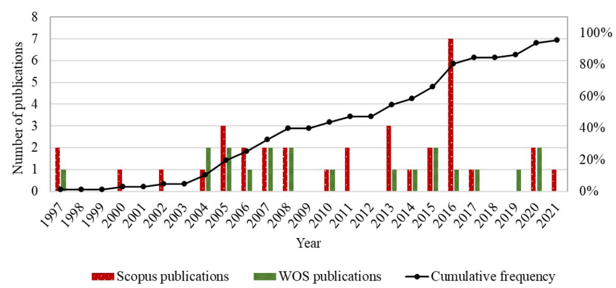

Figure 2. Time evolution of total publications in Scopus and WOS databases.

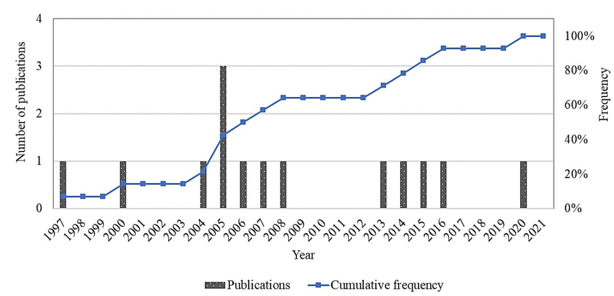

Figure 3. Temporal distribution of scientific production of secondary data.

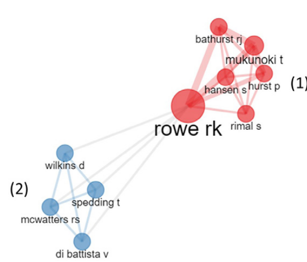

Figure 4. Network collaboration between the main authors with (1) the highest number of publications on the topic; and (2) the lowest number of publications on the topic.

3.4 Countries that publish the most on the topic

An analysis of the countries that have publications on the subject was carried out and a total of 5 countries involved in the research were verified. The emphasis is given to Canada, which has 11 of the 14 publications representing the portfolio, which corresponds to 79% of the total publications. Followed by Japan with 4 publications, Australia with 2, Belgium, Iran and Italy with 1 publication each. Figure 5 represents the geographic distribution of the analyzed studies.

Exploring the articles, it was observed two significant research groups composed of institutions from more than one country. One of them resulted from the co-authors union from institutions in Canada and Japan, and the other was formed by the relations between institutions in Canada and Australia. In this regard, it was noticed that 50% of the articles that have more than one author were developed in partnership with foreign institutions.

Canada had the highest number of publications involving GCLs and permeation with fuels. Some important studies were developed in Canada by one of these groups, specifically in the Canadian radar region on Brevoort Island, located in northern Canada, because of a cleanup program initiated in the summer of 2001 by the Canadian Department of National Defence in consequence of spills and fuel leaks at the site (Rowe et al., 2004; Rowe et al., 2005b; Rowe et al., 2007; Mukunoki et al., 2005; Bathurst et al., 2006; Hosney & Rowe, 2014).

As part of the cleanup program, the alternative built to control the contamination plume was a subsurface geosynthetic composite barrier wall, composed of needle-punched and non-woven GCL with sodium bentonite, HDPE geomembrane, protection layer with needle-punched geotextile and local filling material, constructed during the summer of 2001 (Li et al., 2002; Bathurst et al., 2006).

With regards to the other group of researchers from different countries, Tin et al. (2009) report that several stations in Antarctica have soils contaminated with hydrocarbons due to fuel spills over the years. The strategy developed to remediate the contaminated soil with hydrocarbons was through the construction of biopiles, composed of GCL, HDPE geomembrane and geotextiles, installed over 2011-2013 (McWatters et al., 2016; McWatters et al., 2020).

3.5 Journals where scientific research has been published

The articles that comprise the portfolio of work were distributed in seven journals (not counting the three publications in congresses, conferences and symposia), as shown in Figure 6. The journals “Geotextiles and Geomembranes” and “Journal of Geotechnical and Geoenvironmental Engineering” had featured, with 3 publications each. The other journals - “Géotechnique”, “International Journal of Environmental Research”, “Canadian Geotechnical Journal”, “Geosynthetics International”, and “Journal of ASTM International” - contributed with only 1 article each.

Analyzing the two journals with the highest number of publications, “Geotextiles and Geomembranes” is a journal indexed by Elsevier, aimed at disseminating information among researchers, designers, users and manufacturers of geosynthetic materials. By providing a growing base of information, the journal raises general awareness, stimulates further research and assists in the establishment of codes and regulations. The “Journal of Geotechnical and Geoenvironmental Engineering” is a journal indexed by the ASCE Library and covers research in the field of geotechnical engineering practice.

Another indicator analyzed and represented in Figure 6 was the impact factor (IF) of the mentioned journals, based on the most recent year available (2021). This factor corresponds to a measure of evaluation of journals and is based on citations received, considering publications for the same period, normally one year. Clarivate annually publishes the Journal Citation Report (JCR) with journal impact factor values.

In this case, it is possible to verify that one of the journals - “Geotextiles and Geomembranes” - with the highest number of publications also has a higher impact factor (FI = 5.839). The other journal that also presented the highest number of publications - “Journal of Geotechnical and Geoenvironmental Engineering” exhibited only the fourth highest impact factor (FI = 2.032), with a value very close to the journals that presented only one publication. The journal “Géotechnique”, which, despite having only one publication, has the second highest impact factor (FI = 5.070) and the “International Journal of Environmental Research” with the third highest impact factor (FI = 3.160).

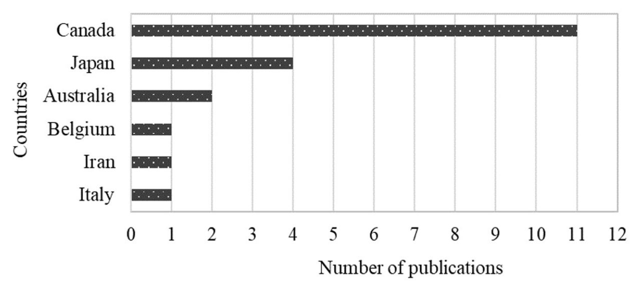

Figure 5. List of countries with publications on the subject.

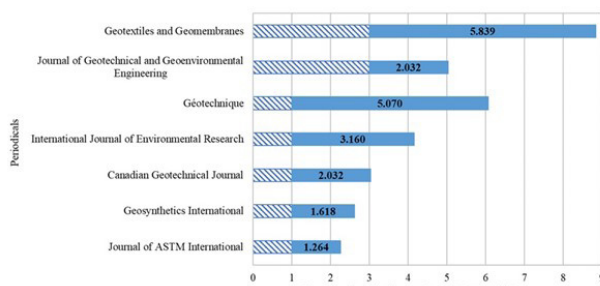

Figure 6. Periodicals with publications on the subject and the respective impact factors.

3.6 Frequency of terms

Determining the frequency of words used in publications is one of the ways to analyze the set of works that make up the bibliographic portfolio, and it can be given through the construction of a word cloud, as illustrated in Figure 7a. The cloud presents the most used terms in the scientific texts under study, and the font size of the word is proportional to the frequency with which they appear.

To assess the relationships between the most frequently identified terms, a thematic map was made, as shown in Figure 7b, which ramifies the terms by similarity and groups them according to their relationships in the texts. Figure 7 was generated with the help of the Biblioshiny interface of the Bibliometrix/R software.

It is observed that the highlight of the cloud is the word "GCL" and its similar ones. The cloud was built with 1-term words/expressions, so the expression "geosynthetic clay liners" is being considered by the word "GCL", for example. The word "GCL" had approximately 73 counts, representing 14% of the total of the 30 most frequent words. Then we have the words that make up the expression "hydraulic conductivity", which together represent 15% of the total, with "hydraulic" and "conductivity" having 43 and 37 counts each, respectively. The emphasis of these words is justified by the fact that they represent the keywords used in the research in the databases.

Next come the words "jet" and "water", each representing 5% of the total frequency. The word "jet" is in evidence because it is the nomenclature of a type of diesel, common in the Canadian arctic regions, where most of the studies were carried out, and the word "water" is quite frequent due to its use as a reference liquid in permeability tests. The same justification given for the word "jet" can also be associated with the expression "freeze and thaw cycles" (composed of the words "cycles" and the expression "freeze_thaw") which, due to the arctic climate where the GCL was exposed and tested, these cycles were considered in the studies. In addition to these two terms, each representing 4% of the total frequency, the words "geomembrane", "specimens" and "fuel" are also found in this range. The other words follow less frequently (less than 20 counts in the publications).

From the thematic map, it is possible to observe the grouping of words into three large niches (Figure 7b). Group 1 includes words that represent basic, emerging themes, with a degree of central relevance, especially the terms "gcl", "hydraulic" and "clay". Group 2 represents the motor themes, with emphasis on the words "conductivity", "liner" and "jet", presenting a degree of development and relevance. Group 3, on the other hand, combines the terms that present more niche themes, with a low-density degree of development, especially the words "performance", "conditions" and "hydrocarbons".

In general, it is possible to highlight that the elaboration of the word cloud and the thematic map complements what was previously observed, about most of the works on containment barriers for fuels with GCL being concentrated on a specific research group, seen by the highlight observed in words and expressions related to climate issues and type of fuel, typical of the places where the research was carried out.

3.7 Thematic synthesis

The bibliometric research carried out on the evaluation of the hydraulic conductivity of protective barriers for fuels with GCL revealed that it is a topic of interest to a limited group of researchers. The indices pointed to several studies on the hydraulic behavior of GCL in containment barriers for the spills of Jet A-1 diesel, a common fuel in the Canadian arctic regions. As the work was concentrated in these extreme climate regions, the freezing and thawing cycles of the geosynthetic were also objectives of these studies.

Petrov et al. (1997) examined the hydraulic conductivity of hydrated GCLs permeated with different concentrations of water and ethanol solutions. Mazzieri et al. (2000) also evaluated the hydraulic conductivity of GCLs with various ethanol solutions in water, performing tests on hydrated and unhydrated GCLs.

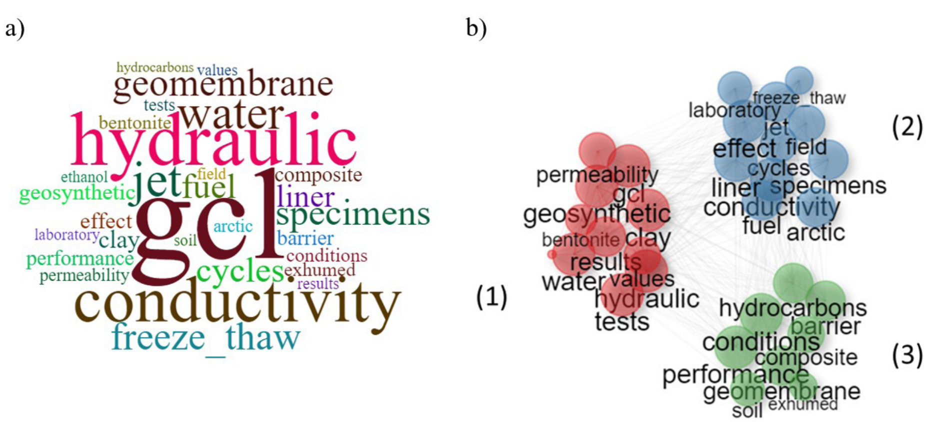

Figure 7. Frequency of the most used words in publications (a) and their interrelationships (b) through clusters of (1) basic, emerging, and central relevant terms; (2) driving terms; and (3) low-density terms.

Sari & Chai (2013) investigated self-healing capacity of GCLs with respect to different liquids permeation, including ethanol, considering circular induced damages. Rowe et al. (2004), Mukunoki et al. (2005), Rowe et al. (2006) and Rowe et al. (2008) presented results on the performance of GCLs used in temporary containment barriers for fuel spills of Jet A-1, considering the freeze and thaw cycles in laboratory investigation and exhumation of samples in different periods of exposition in the field. Rowe et al. (2005a), Rowe et al. (2005b) and Rowe et al. (2007) studied the hydraulic behavior of GCLs in the laboratory with respect to jet fuel A-1 for saturated and unsaturated conditions, also considering temperature variations. Hosney & Rowe (2014) conducted research on the hydraulic conductivity of samples extracted from the field over 10 years, exposed to arctic diesel contact, at different depths. Gitipour et al. (2015) performed permeability tests on bentonites sandwiched between geotextiles, which simulate a sample of GCL, with respect to permeation of water and crude oil. McWatters et al. (2016) and McWatters et al. (2020) evaluated the hydraulic performance of biopiles developed to contain and remediate soil contaminated by hydrocarbons and leachate in Antarctica.

A decade ago, Rowe et al. (2008) found that little attention had been paid to permeability studies of GCLs with hydrocarbons. Through the portfolio of the present research, it is observed that there has been no significant growth in the number of publications related to the theme over the years, until today.

The Table 1 presents the synthesis of the main data from these articles obtained on hydraulic conductivity of GCLs permeated with fuels, published over the years.

Table 1. Results from published research on hydraulic conductivity of GCLs in contact with fuels.

Reference	Main Points		Permeameter type	Hydraulic conductivity *k* (distilled/de-aired/de-ionized water / *tap water*)			Hydraulic conductivity *k* (fuel)			
	General	Specifics		Freeze-thaw cycles (n); *Exposure time*	*k* Virgin (m/s) [σ' (kPa)]	*k* Exhumed (m/s) [σ' (kPa)]	Fuel type	Freeze-thaw cycles (n); *Exposure time*	*k* Virgin (m/s) [σ' (kPa)]	*k* Exhumed (m/s) [σ' (kPa)]
Petrov et al., 1997	Ethanol/water mixtures		Fixed-WP		6.0×10^{-11} [4]		100% ethanol		2.0×10^{-9} [35]	
					1.3×10^{-11} [35]		75% ethanol		4.1×10^{-11} [35]	
					7.5×10^{-12} [114]		50% ethanol		6.0×10^{-12} [35]	
					1.6×10^{-11} [35]		25% ethanol		7.3×10^{-12} [35]	
Mazzieri et al., 2000	Ethanol/water mixtures	Water-hydrated GCL	FWP		1.0×10^{-11} [50]		100% ethanol		1.0×10^{-10} [50]	
		Ethanol-hydrated GCL					100% ethanol		5.5×10^{-8} [50]	
							75% ethanol		5.5×10^{-8} [50]	
							50% ethanol		3.5×10^{-10} [50]	
							25% ethanol		3.0×10^{-11} [50]	
Rowe et al., 2004	Canadian Arctic; Hydrocarbon spill	Freeze-thaw cycles	FWP	0	8.3×10^{-11} [1.4]		Jet Fuel A-1	0	4.3×10^{-12} [14]	
					4.0×10^{-11} [14]					
				5	6.3×10^{-11} [1.4]			6	8.7×10^{-12} [14]	
					2.9×10^{-11} [14]					
				12	4.3×10^{-11} [1.4]			12	2.7×10^{-10} [14]	
					2.3×10^{-11} [14]					
				1 year		4.0×10^{-11} [1.4]		13	5.6×10^{-12} [14]	
						2.0×10^{-11} [14]				
Mukunoki et al., 2005	Canadian Arctic; Hydrocarbon spill	Freeze-thaw cycles	RWP	0	2.0×10^{-11} [14]		Jet Fuel A-1	0	2.0×10^{-11} [14]	
				5	2.0×10^{-11} [14]			5	8.0×10^{-11} [14]	
				3 years		7.1×10^{-12} [14]		*3 years*		3.6×10^{-11} [14]
Rowe et al., 2005a	Canadian Arctic; Laboratory investigation	5°C	Fixed-WP		1.0×10^{-11} [14]		Jet Fuel A-1		4.1×10^{-11} [14]	
		5°C; w_c=60%							1.6×10^{-9} [14]	
		5°C; w_c=90%							1.7×10^{-9} [14]	
		5°C; w_c=120%							1.2×10^{-9} [14]	
		-5°C; w_c=60%							1.3×10^{-9} [14]	
		-5°C; w_c=90%							0.4×10^{-9} [14]	
		-5°C; w_c=120%							0.4×10^{-9} [14]	
		-5°C							$< 1.3 \times 10^{-12}$ [14]	
		5°C; 1 freeze							4.1×10^{-10} [14]	
		0 < T < 20°C; S_r=77%							$\leq 3.0 \times 10^{-10}$ [14]	
		0 > T > -20°C; S_r=70%							$\leq 2.5 \times 10^{-10}$ [14]	

FWP – flexible wall permeameter; RWP – rigid wall permeameter; Fixed-WP – fixed-wall permeameter; n – quantity of freeze-thaw cycles; w_c – moisture content; S_r – saturation degree; GCL – geosynthetic clay liner; GTX – geotextile; k – hydraulic conductivity; σ' – effective confining stress.

Table 1. Continued...

Reference	Main Points: General	Main Points: Specifics	Permeameter type	Hydraulic conductivity k (distilled/de-aired/de-ionized water / *tap water*): Freeze-thaw cycles (n); *Exposure time*	k Virgin (m/s) [σ' (kPa)]	k Exhumed (m/s) [σ' (kPa)]	Hydraulic conductivity k (fuel): Fuel type	Freeze-thaw cycles (n); *Exposure time*	k Virgin (m/s) [σ' (kPa)]	k Exhumed (m/s) [σ' (kPa)]
Rowe et al., 2006	Canadian Arctic; Hydrocarbon spill		RWP	0	2.0×10^{-11} [15]		Jet Fuel A-1	0	2.0×10^{-11} [15]	
				5	2.0×10^{-11} [15]			5	8.0×10^{-11} [15]	
				12	2.6×10^{-11} [15]			12	1.5×10^{-10} [15]	
				1 year		1.2×10^{-11} [15]		*1 year*		7.1×10^{-11} [15]
				3 years		0.7×10^{-11} [15]		*3 years*		5.3×10^{-11} [15]
Rowe et al., 2005b;	Canadian Arctic; Laboratory investigation		RWP	0	2.0×10^{-11} [14]		Jet Fuel A-1	0	2.0×10^{-11} [14]	
				5	2.0×10^{-11} [14]			5	8.0×10^{-11} [14]	
			FWP	0	3.4×10^{-11} [14]			0	4.0×10^{-11} [14]	
				12	3.4×10^{-11} [14]			12	6.0×10^{-11} [14]	
Rowe et al., 2007		20°C; S_r=60%	RWP						1.6×10^{-8} [14]	
		5°C; S_r=60%							1.6×10^{-9} [14]	
		-5°C; S_r=60%							2.4×10^{-10} [14]	
		-20°C; S_r=60%							2.8×10^{-11} [14]	
		20°C; S_r=90%							3.4×10^{-10} [14]	
		5°C; S_r=90%							1.4×10^{-9} [14]	
		-5°C; S_r=90%							9.0×10^{-11} [14]	
		-20°C; S_r=90%							1.8×10^{-11} [14]	
Rowe et al., 2008	Canadian Arctic; Hydrocarbon spill	Contrast with Rowe et al. (2006)	FWP	0	3.3×10^{-11} [13]		Jet Fuel A-1	0	< 7.8×10^{-11} [23-41]	
				5	4.3×10^{-11} [13]			5	< 2.6×10^{-11} [17-20]	
				12	3.1×10^{-11} [13]			12	< 7.9×10^{-11} [20-30]	
				50	5.3×10^{-11} [13]			50	< 1.5×10^{-10} [17-27]	
				100	3.6×10^{-11} [13]			100	< 3.4×10^{-10} [13-20]	
				3 years		2.3×10^{-11} [13]		*3 years*		< 3.3×10^{-11} [17-27]
Hosney & Rowe, 2014	Canadian Arctic;Hydrocarbon spill		FWP		*3.8×10^{-11} [15]*		Jet Fuel A-1		6.2×10^{-12} [15]	
		Trench; Depth: 0.8 m		*1 year*		*2.6×10^{-11} [15]*		*1 year*		3.3×10^{-12} [15]
		Trench; Depth: 0.8 m		*4 years*		*4.0×10^{-11} [15]*		*4 years*		2.7×10^{-11} [15]
		Frame; Depth: 1.5-2.3 m		*6 years*		*3.1×10^{-10} [15]*		*6 years*		1.4×10^{-9} [15]
		Frame; Depth: 0-0.5 m		*7 years*		*3.0×10^{-11} [15]*		*7 years*		3.5×10^{-11} [15]
		Frame; Depth: 0.8-1.3 m		*10 years*		*3.9×10^{-10} [15]*		*10 years*		3.2×10^{-10} [15]
Gitipour et al., 2015	Simulated GCL; GTX + Bentonite + GTX		RWP		9.6×10^{-13}		Crude oil		1.2×10^{-8}	
					-				-	
McWatters et al., 2016	Antarctica; Biopiles; Hydrocarbon spill	w_c=13%	FWP		*4.0×10^{-11} [13]*					
		w_c=162%		*3 years*		*3.1×10^{-11} [13]*				
		w_c=22%		*3 years*		*3.0×10^{-11} [13]*				
McWatters et al., 2020	Antarctica; Biopiles; Hydrocarbon spill	w_c=12%	FWP		*1.5×10^{-11} [13]*					
		w_c=10%		*4 years*		*3.6×10^{-11} [13]*				
		w_c=200%		*4 years*		*3.9×10^{-11} [13]*				

FWP – flexible wall permeameter; RWP – rigid wall permeameter; Fixed-WP – fixed-wall permeameter; n – quantity of freeze-thaw cycles; w_c – moisture content; S_r – saturation degree; GCL – geosynthetic clay liner; GTX – geotextile; k – hydraulic conductivity; σ' – effective confining stress.

4. Conclusion

The present research aimed to evaluate the scientific production on the hydraulic conductivity of GCL in contact with fuels through a quantitative and descriptive analysis. The study provided an overview of the publications, authors, countries, and journals that published the most on the subject. The analyzed databases, Scopus and Web of Science, presented similar consistency and bibliographic coverage regarding the theme, since most of the articles were found in both bases, proving to be efficient research tools.

The bibliometric review identified that the scientific production on the subject is limited to a small number of articles, with a total of 14 articles forming the bibliographic portfolio. Through a critical analysis of these studies, several knowledge gaps and opportunities for future research were identified. The main contributions of this review study, including the synthesis of key results and the identification of general trends in the research area, are of great importance to the scientific community. Additionally, the bibliometric indicators obtained in this study indicate that this is a promising area for further research, given the limited scientific production found on the topic.

As already mentioned, GCL can be used as an hydraulic barrier in places where there is movement and distribution of fuels, in storage tanks and to contain some type of accidental spillage, to avoid contact and percolation of fuel towards the subsoil and groundwater waters. Therefore, it is important to pay attention to the development of research in the area aimed at clarifying the behavior of the hydraulic conductivity of GCL in contact with fuels, ensuring the efficiency of the barrier.

The collected data show that the number of publications related to the studied topic did not increase significantly over the years. Most studies were conducted by the same research group, indicating that more researchers should be encouraged to explore this area.

The study achieved its objective of expanding readers' knowledge about the scientific collection related to the use of GCL in fuel hydraulic containment systems, as well as the hydraulic conductivity of the geosynthetic in contact with these contaminants. Through the collected data, the study established indicators that allow the researcher to select and analyze existing publications, directing their future research in order to contribute to the scientific development of the area.

Acknowledgements

The authors desire to express their gratitude to CNPq (Grant n. 314643/2020-6), to the Graduate Program in Civil and Environmental Engineering of the University of Passo Fundo, and to the Geotechnical Laboratory of the Technological Center for Civil, Environmental Engineering and Architecture, at the same university, which enabled the development of practical experiments to compare the information collected in the respective study.

Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Julia Favretto: project administration, supervision, conceptualization, data curation, investigation, validation, visualization, writing – original draft. Adeli Beatriz Braun: conceptualization, data curation, investigation, methodology, visualization, writing – original draft. Márcio Felipe Floss: formal analysis, supervision, validation. Pedro Domingos Marques Prietto: formal analysis, supervision, validation.

Data availability

All data produced or examined in the course of the current study are included in this article.

References

Bathurst, R.J., Rowe, R.K., Zeeb, B., & Reimer, K. (2006). A geocomposite barrier for hydrocarbon containment in the Arctic. *International Journal of Geoengineering Case Histories*, 1(1), 18-34.

Bouazza, A. (2002). Geosynthetic clay liners. *Geotextiles and Geomembranes*, 20(1), 3-17. http://dx.doi.org/10.1016/S0266-1144(01)00025-5.

Bouazza, A., & Vangpaisal, T. (2007). Gas permeability of GCLs: effect of poor distribution of needle punched fibres. *Geosynthetics International*, 14(4), 248-252. http://dx.doi.org/10.1680/gein.2007.14.4.248.

Bouazza, A., Rouf, M.A., Singh, R.M., Rowe, R.K., & Gates, W.P. (2017). Gas advection-diffusion in geosynthetic clay liners with powder and granular bentonites. *Geosynthetics International*, 24(6), 607-614. http://dx.doi.org/10.1680/jgein.17.00027.

Bouazza, A., Vangpaisal, T., & Jefferis, S. (2006). Effect of wet-dry cycles and cation exchange on gas permeability of geosynthetics clay liners. *Journal of Geotechnical and Geoenvironmental Engineering*, 132(8), 1011-1018. http://dx.doi.org/10.1061/(ASCE)1090-0241(2006)132:8(1011).

Bradshaw, S.L., & Benson, C.H. (2013). Effect of municipal solid waste leachate on hydraulic conductivity and exchange complex of geosynthetic clay liners. *Journal of Geotechnical and Geoenvironmental Engineering*, 140(4), 04013038. http://dx.doi.org/10.1061/(ASCE)GT.1943-5606.0001050.

Braun, A.B., Trentin, A.W.S., Visentin, C., & Thomé, A. (2019). Sustainable remediation through the risk management perspective and stakeholder involvement: a systematic and bibliometric view of the literature. *Environmental Pollution*, 255, 113221. http://dx.doi.org/10.1016/j.envpol.2019.113221.

Carnero-Guzman, G.G., Bouazza, A., Gates, W.P., Rowe, R.K., & McWatters, R. (2021). Hydration/dehydration behavior of geosynthetic clay liners in the Antarctic environment. *Geotextiles and Geomembranes*, 49(1), 196-209. http://dx.doi.org/10.1016/j.geotexmem.2020.10.020.

Gitipour, S., Hosseinpour, M.A., Heidarzadeh, N., Yousefi, P., & Fathollahi, A. (2015). Application of modified clays in geosynthetic clay liners for containment of petroleum contaminated sites. *International Journal of Environmental Research*, 9(1), 317-322. http://dx.doi.org/10.22059/IJER.2015.903.

Hewitt, R.D., & Daniel, D.E. (1997). Hydraulic conductivity of geosynthetic clay liners after freeze-thaw. *Journal of Geotechnical and Geoenvironmental Engineering*, 123(4), 305-313. http://dx.doi.org/10.1061/(ASCE)1090-0241(1997)123:4(305).

Hosney, M.S., & Rowe, R.K. (2014). Performance of GCL after 10 years in service in the Arctic. *Journal of Geotechnical and Geoenvironmental Engineering*, 140(10), 04014056. http://dx.doi.org/10.1061/(ASCE)GT.1943-5606.0001160.

Koerner, R.M. (2012). *Designing with geosynthetics* (6th ed., Vol. 2). Bloomington: Xlibris Corporation.

LaGatta, M.D., Boardman, B.T., Cooley, B.H., & Daniel, D.E. (1997). Geosynthetic clay liners subjected to differential settlement. *Journal of Geotechnical and Geoenvironmental Engineering*, 123(5), 402-410. http://dx.doi.org/10.1061/(ASCE)1090-0241(1997)123:5(402).

Lake, C.B., & Rowe, R.K. (2000). Swelling characteristics of needlepunched thermally treated geosynthetic clay liners. *Geotextiles and Geomembranes*, 18(2), 77-101. http://dx.doi.org/10.1016/S0266-1144(99)00022-9.

Li, H.M., Bathurst, R.J., & Rowe, R.K. (2002). Use of GCLs to control migration of hydrocarbons in severe environmental conditions. In H. Zanzinger, R.M. Koerner & E. Gartung (Eds.), *Clay geosynthetic barriers* (pp. 187-198). London: CRC Press. https://doi.org/10.1201/9781003078777-22.

Macedo, M., Botelho, L.L.R., & Duarte, M.A.T. (2010). Revisão bibliométrica sobre a produção científica em aprendizagem gerencial. *Gestão e Sociedade*, 4(8), 619-639. http://dx.doi.org/10.21171/ges.v4i8.999.

Mazzieri, F., Pasqualini, E., & Van Impe, W.F. (November 19-24, 2000). Compatibility of GCLs with organic solutions. In International Society for Rock Mechanics (Ed.), *ISRM International Symposium* (pp. ISRM-IS-2000-001). Lisbon: International Society for Rock Mechanics.

McWatters, R.S., Rowe, R.K., Battista, V., Sfiligoj, B., Wilkins, D., & Spedding, T. (2020). Exhumation and performance of an Antarctic composite barrier system after 4 years exposure. *Canadian Geotechnical Journal*, 57(8), 1130-1152. http://dx.doi.org/10.1139/cgj-2018-0715.

McWatters, R.S., Rowe, R.K., Wilkins, D., Spedding, T., Jones, D., Wise, L., Mets, J., Terry, D., Hince, G., Gates, W.P., Di Battista, V., Shoaib, M., Bouazza, A., & Snape, I. (2016). Geosynthetics in Antarctica: performance of a composite barrier system to contain hydrocarbon-contaminated soil after three years in the field. *Geotextiles and Geomembranes*, 44(5), 673-685. http://dx.doi.org/10.1016/j.geotexmem.2016.06.001.

Meer, S.R., & Benson, C.H. (2007). Hydraulic conductivity of geosynthetic clay liners exhumed from landfill final covers. *Journal of Geotechnical and Geoenvironmental Engineering*, 133(5), 550-563. http://dx.doi.org/10.1061/(ASCE)1090-0241(2007)133:5(550).

Mukunoki, T., Rowe, R.K., Hurst, P., & Bathurst, R.J. (2005). Application of geosynthetic barrier wall to containment of hydrocarbons in the Arctic. In Organizing Committee of the 16th International Conference on Soil Mechanics and Geotechnical Engineering (Ed.), *Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering: Geotechnology in Harmony with the Global Environment* (pp. 2415-2418). Amsterdam, The Netherlands: IOS Press. https://doi.org/10.3233/978-1-61499-656-9-2415.

Petrov, R.J., Rowe, R.K., & Quigley, R.M. (1997). Selected factors influencing GCL hydraulic conductivity. *Journal of Geotechnical and Geoenvironmental Engineering*, 123(8), 683-695. http://dx.doi.org/10.1061/(ASCE)1090-0241(1997)123:8(683).

Rowe, R.K. (2012). Short and long-term leakage through composite liners. The 7th Arthur Casagrande Lecture. *Canadian Geotechnical Journal*, 49, 141-169. http://dx.doi.org/10.1139/t11-09.

Rowe, R.K. (2014). Performance of GCLs in liners for landfill and mining applications. *Environmental Geotechnics*, 1(1), 3-21. http://dx.doi.org/10.1680/envgeo.13.00031.

Rowe, R.K. (2020). Geosynthetic clay liners: perceptions and misconceptions. *Geotextiles and Geomembranes*, 48(2), 137-156. http://dx.doi.org/10.1016/j.geotexmem.2019.11.012.

Rowe, R.K., & AbdelRazek, A.Y. (2021). Performance of multicomponent GCLs in high salinity impoundment applications. *Geotextiles and Geomembranes*, 49(2), 358-368. http://dx.doi.org/10.1016/j.geotexmem.2020.10.007.

Rowe, R.K., Brachman, R.W.I., Take, W.A., Rentz, A., & Ashe, L.E. (2016). Field and laboratory observations of down-slope bentonite migration in exposed composite liners. *Geotextiles and Geomembranes*, 44(5), 686-706. http://dx.doi.org/10.1016/j.geotexmem.2016.05.004.

Rowe, R.K., Garcia, J.D., Brachman, R.W.I., & Hosney, M.S. (2019). Hydraulic and chemical performance of geosynthetic clay liners isothermally hydrated from silty sand subgrade. *Geotextiles and Geomembranes*, 47(6), 740-754. http://dx.doi.org/10.1016/j.geotexmem.2019.103486.

Rowe, R.K., Hurst, P., & Mukunoki, T. (2005a). Permeating partially hydrated GCLs with jet fuel at temperatures from -20 °C and 20 °C. *Geosynthetics International*, 12(6), 333-343. http://dx.doi.org/10.1680/gein.2005.12.6.333.

Rowe, R.K., Mukunoki, T., & Bathurst, R.J. (2006). Compatibility with Jet A-1 of a GCL subjected to freeze thaw cycles. *Journal of Geotechnical and Geoenvironmental Engineering*, 132(12), 1526-1537. http://dx.doi.org/10.1061/(ASCE)1090-0241(2006)132:12(1526).

Rowe, R.K., Mukunoki, T., & Bathurst, R.J. (2008). Hydraulic conductivity to Jet-Al of GCLs after up to 100 freeze-thaw cycles. *Geotechnique*, 58(6), 503-511. http://dx.doi.org/10.1680/geot.2008.58.6.503.

Rowe, R.K., Mukunoki, T., Bathurst, R.J., Rimal, S., Hurst, P., & Hansen, S. (January 24-26, 2005b). The performance of a composite liner for retaining hydrocarbons under extreme environmental conditions. In M. Gabr, J. J. Bowders, D. Elton & J. G. Zornberg (Eds.), *Geo-Frontiers Congress 2005* (pp. 2795-2811). Reston, USA: American Society of Civil Engineers. https://doi.org/10.1061/40787(166)16.

Rowe, R.K., Mukunoki, T., Bathurst, R.J., Rimal, S., Hurst, P., & Hansen, S. (2007). Performance of a geocomposite liner for containing Jet A-1 spill in an extreme environment. *Geotextiles and Geomembranes*, 25(2), 68-77. http://dx.doi.org/10.1016/j.geotexmem.2006.10.003.

Rowe, R.K., Mukunoki, T., Li, M.H., & Bathurst, R.J. (2004). Effect of freeze-thaw on the permeation of arctic diesel through a GCL. In R.E. Mackey & K.P. von Maubeuge (Eds.), *Advances in geosynthetic clay liner technology* (pp. 134-146). West Conshohocken: ASTM International. http://dx.doi.org/10.1520/STP12203S.

Sari, K., & Chai, J. (2013). Self healing capacity of geosynthetic clay liners and influencing factors. *Geotextiles and Geomembranes*, 41, 64-71. http://dx.doi.org/10.1016/j.geotexmem.2013.08.006.

Scopus. (2022). *Quick reference guide*. Retrieved in 2022, August 16, from https://www.scopus.com/

Tin, T., Fleming, Z.L., Hughes, K.A., Ainley, D.G., Convey, P., Moreno, C.A., Pfeiffer, S., Scott, J., & Snape, I. (2009). Impacts of local human activities on the Antarctic environment. *Antarctic Science*, 21, 3-33. http://dx.doi.org/10.1017/S0954102009001722.

Touze-Foltz, N., Duquennoi, C., & Gaget, E. (2006). Hydraulic and mechanical behavior of GCLs in contact with leachate as part of a composite liner. *Geotextiles and Geomembranes*, 24, 188-197. http://dx.doi.org/10.1016/j.geotexmem.2006.01.004.

Viana, P.M.F., Palmeira, E.M., & Viana, H.N.L. (2011). Evaluation on the use of alternative materials in geosynthetic clay liners. *Soils and Rocks*, 34(1), 65-77. http://dx.doi.org/10.28927/SR.341065.

Visentin, C., Trentin, A.W.S., Braun, A.B., & Thomé, A. (2020). Life cycle sustainability assessment: a systematic literature review through the application perspective, indicators, and methodologies. *Journal of Cleaner Production*, 270, 122509. http://dx.doi.org/10.1016/j.jclepro.2020.122509.

Wang, B., Xu, J., Chen, B., Dong, X., & Dou, T. (2019). Hydraulic conductivity of geosynthetic clay liners to inorganic waste leachate. *Applied Clay Science*, 168, 244-248. http://dx.doi.org/10.1016/j.clay.2018.11.021.

Web of Science. (2022). *Quick reference guide*. Retrieved in 2022, August 16, from https://clarivate.com/webofsciencegroup/