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Original Research

Landfill Liner Composite Materials: Bibliometric and Content Analysis

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Abstract

The use of liners as leachate retainers in landfills, which is the final stage of waste processing, has become a global trend. Recently, researchers of the materials used as retainers have aimed to find the best materials while minimizing losses from landfills. As such, in this study, we conducted a comprehensive review to determine trends, evolutions, key research areas, and future research paths in this field. Our findings serve as a reference for advancing progress in landfill liner research. We used bibliometric and content analyses of the field in the literature from 2011 to 2021. We analyzed a total of 385 articles from the Scopus database using the Vos Viewer application. We concluded that this topic has received considerable in the 10-year period. From the 142 keywords and 5 clusters we obtained, we found that the most attention was paid to geosynthetic and geomembrane materials. We provide several recommendations that can be addressed in future research.

Keywords: landfill liner, bibliometric, content analysis, VosViewer, geosynthetic

Introuction

The increase in population and the concomitant need to fulfill clothing, food, and housing demands are affecting the environment, especially through the production of municipal waste. In their study, Kaza et al. [1] mention that the World Bank Group predicted that, by 2050, municipal waste produced worldwide will reach 3.4 billion tons, and in 2016, it reached 2.1 billion tons. Meeting the needs of countries worldwide may be the primary source of waste. For example, every year, the U.S. produces up to 136 million tons of waste [2]. Indonesia is the largest waste-producing country in Southeast Asia, at 4 million tons per year [3].

Landfills are one method used to minimize waste accumulation, and biodegradable and nonbiodegradable waste are placed in landfills in many locations worldwide. A total of 2000 active landfills are located in the U.S. [4] and Canada [5]. Landfills are the most effective, efficient, and simple infrastructure used for waste control compared with other methods, such as incineration and recycling, which require large investment, especially for maintenance. In addition, landfills provide additional benefits from biogas as an energy generator [6]. According to Powrie et al. [7], the landfill method can be used to safely return residues to the environment if sustainably operated.

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However, the landfill method also has a limitation: the produced leachate can seep, be toxic to groundwater, and lead to biomagnification [8]. In addition, according to Rezaeisabzevar et al. [9], reported that the leachate produced in the long term is toxic, thus affects landfill construction sites. Leachate is a liquid that has external sources, including waste decomposition, drainage, and rain, and enters landfills [10]. Hou et al. [11] reported that liners can be used to minimize leachate contamination in landfills.

Liners have been used in landfills since the 1980s and are an essential component of modern landfill systems. First, the compacted clay layer (CCL) was commonly used as a liner. In the late 1980s, geomembranes (GMs) replaced the CCL, and with advancements in the early 1990s, the geosynthetic clay liner (GCL) became more widely used. A GM is a layer of clay covered by a GM, whereas the GCL is covered by a geosynthetic material. GCLs are more popular than CCLs because of their low hydraulic conductivity, mechanical behavior, self-healing capacity, and easier installation [12-19]. In addition, large holes may form in GMs [20, 21]. Therefore, Rowe [22], AFNOR [23] mentioned that GCL is commonly used in civil engineering and geotechnical engineering to prevent fluid seepage into construction, and is assisted by clay as a barrier.

Despite the widespread application of GCL in the field, the method also has weaknesses; Pires et al. [24], Özbay [25], Zhang et al. [26], Yang et al. [27] reported that middle-income countries experience limitations in the use of geosynthetic soil coatings, GMs, etc., owing to the need for sophisticated materials and equipment. Zurbrügg et al. [28] found that the technology and skills of local technicians affect the technical sustainability of landfills, so the use of locally available and affordable materials can be a concern. The availability of the clay used as a liner is often limited. Artificial coating systems, such as GMs, are less affordable at USD 24,000-35,000 and USD 33,000-44,000 [29].

Hypersalinity and extreme weather have encouraged research on the effects of landfill liner exposure to the environment [30]. Therefore, the selection of materials for use in landfills must focus on their impact on ecology and the environment to ensure sustainable landfills are created. The use of artificial clays and coatings should also be reduced as they consume large amounts of natural resources. Some of these reasons have led to the development of alternative materials for liners using waste, such as coal, rubber, and plastic waste. Several researchers have examined the feasibility of the use these waste materials, including the compressive and tensile strengths of fly ash-bentonite composites [31, 32] and the desiccation test of waste tire textile fibers [33]. Vandecasteele and van der Sloot [34] stated that using waste as a substitute for clay is a substantial resource saving method, as it converts waste into energy and recyclesLandfill liner composite materials have now become a research hotspot in recent years. Research on this topic has been done by various scientists, such as Kong et al. [30], Narani et al. [33], Rubinos and Spagnoli [35], etc. However, research from a bibliometric perspective is scarce, such as the study by Wang et al. [36] who investigated the trends and performance of landfill Research from 1999 to 2013 using bibliometric analysis. Reshadi et al. [37] reported the evolving trends in landfill leachate treatment research over a 45-year period. Bibliometrics is a review that identifies trends in specific themes, such as publication years, countries, authors, theories, and methods from available information [38]. Bibliometric analysis is a source of information for evaluating scientific activities [39, 40], from which recommendations for further research can be formulated.

Therefore, in this study, we aimed to comprehensively review and determine trends or evolution, key research areas, and future research paths in the field of landfill liner materials for a 10-year period. Our findings will serve as a reference for further research on landfill liners. In addition, we analyzed the content of the 10 most influential articles. According to Jia and Jiang [41], content analysis acts as a qualitative complement to provide an in-depth overview of and insight into research. We structure the remainder of this paper as follows: Section 2 presents our research methods (collection, processing, and analysis of data). Section 3 outlines a bibliometric mapping that considers articles from 2011 to 2021 and our content analysis of the 10 most influential or most-cited articles. We also describe the gaps in the literature and provide a general overview for future research in Section 4, including our conclusions.

Materials and Methods

The research methodology, as shown in Fig. 1, consisted of three stages: First, we collected data from the Scopus database. Scopus contains more than 60 million articles, 5000 publishers, and 21,500 peer-reviewed articles in various scientific fields, making it the largest repository of citations and abstract databases for authors worldwide [42], which is why we chose this database, with a focus on articles published in 2011-2021 and limited to January 17, 2022. Second, we used a combination of search queries to explore article titles, abstracts, and keywords: “TITLE-ABS-KEY (landfill AND liner AND composite AND material).” We retrieved a total of 698 documents from the initial search. Third, we applied exclusion criteria. First, we applied the year filter; we selected only the documents written in 2011-2021, i.e., a total of 426 articles. Second, a language filter was applied; only documents written in English were selected, which reduced the total to 425 articles. Finally, we selected all articles focusing on the overall landfill liner composite material published in the last 10 years from 2011 to 2021 and used them as the final sample for analysis. We extracted a total of 208 sample articles, including titles, abstracts, keywords, bibliographic information, and citation information, in comma-separated value (CSV) format, from the Scopus database.

The second stage was data processing, where we then cleaned the retrieved CSV format to obtain more valid clean data. We cleaned data using Microsoft Excel by paying attention to and removing blank data, double spacing, and nonuniform spelling. Ranjbari et al. [43] said that data cleaning is the first and fundamental step in the bibliometric analysis.

The third stage involved combined quantitative and qualitative data analyses, consisting of bibliometric and content analyses, to provide a more in-depth picture of the literature. According to Vogel and Güttel [44], bibliometric analysis is an information tracker providing a more structured literature review for a particular research area. We used the VOSviewer application in this study to analyze the co-occurrence, cocitation, and coauthorship networks. Our primary focus was identifying the evolution of publications, collaboration, productivity, citations, and hotspots of related topics over the 10-year period. The VOSviewer application primarily functioned in this study to investigate co-occurrence and main research topics related to landfill liner composite materials. According to Van Eck and Waltman [45], VOSviewer can improve the quality of analysis, and used to clean data and to merge terms, author names, and other bibliographic information. We analyzed the content of ten influential articles to determine the meaning of the text. This quantitative analysis helped us to develop understanding and categories related to the topic and enabled a more systematic content analysis [46].

Result and Discussion

Bibliometric Mapping of Extant Landfill Liner Composite Material Studies

Analysis of Publication Evolution

Fig. 2 plots the trend in publications related to landfill liner composite materials from 2011 to 2021. The results fluctuated but the number of studies tended to increase over the 10 years. The highest increase in publications of 18 documents occurred from 2020 to 2021, from 37 to 55. The studies on landfill liner composite materials have continued to increase, in agreement with previous findings of Reshadi et al. [37].

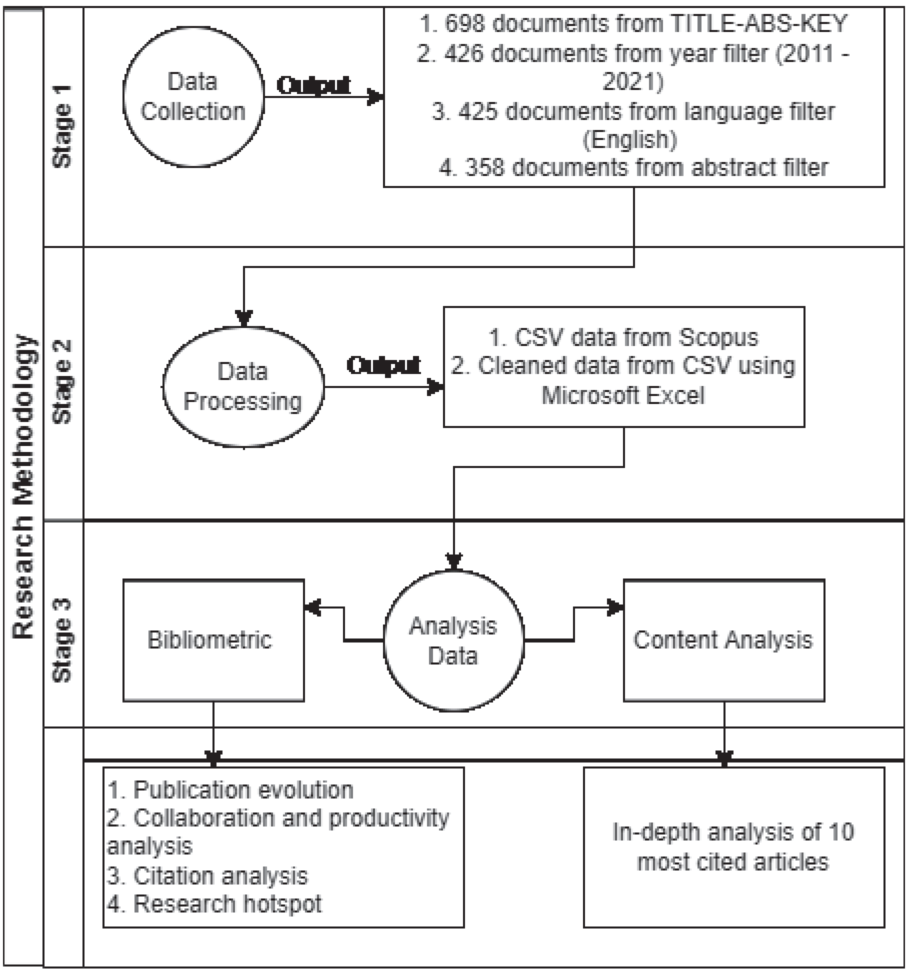

Fig. 1. Research Methodology.

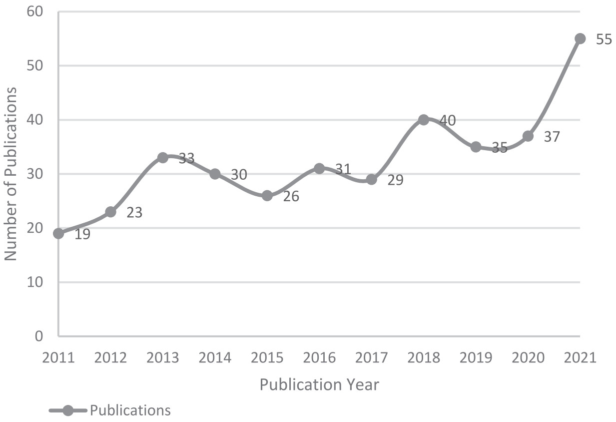

Fig. 2. The annual trends of landfill liner composite material-related publications.

Reshadi et al. [37] reported that due to stricter law enforcement and environmental regulations related to landfill leachate, researchers are actively looking for more efficient alternatives to handle leachate in landfills to meet the standards. A landfill liner is one method of handling leachate seepage in landfills.

The 358 publications were published in 145 journals. However, only 59.3% (86) of journals published one article related to landfill liner composite materials. We found that out of 358 publications, 129 (36%) were published in the top 10 journals. Geotextiles and Geomembranes topped the list of journals, with 26 publications. The journal published many articles related to waterproof membranes, including hazardous leachate retaining liners or municipal waste, showing that many researchers published their findings on liner materials for geotextiles and GMs. A total of 20 articles were published in Continued Journal of Geotechnical and Geoenvironmental Engineering. The lowest position, with six publications, was occupied by the IOP Conference Series: Earth and Environmental Science.

Collaboration and Productivity Analysis

The countries and institutions connected in the network also play a role in determining the direction of future research. China and Canada showed the strongest relationship, as indicated by the thickness of the line connecting nodes (countries) in Fig. 3. This shows that geographical distance has not prevented strong cooperative relationships between countries. China was the most productive country, with 83 publications, as indicated by having the largest nodes and the colors on the map, followed by India (57 publications) and the United States (53 publications). The growth in the number of publications from China may have been related to population growth and the national economy [36]. In addition, according to Reshadi et al. [37], the Chinese government provides considerable support for monitoring water resource pollution due to water scarcity in this developing country. Canada was the most influential country, with 933 citations, followed by China (868 citations), the United States (716 citations), India (294 citations), and France (228 citations).

Table 1 provides the data from the most productive and influential institutions related to the publication of studies on landfill liner composite materials. Queen's University Canada was the most productive institute, with seven publications. The most influential institution was the same, with Queen's University in Canada

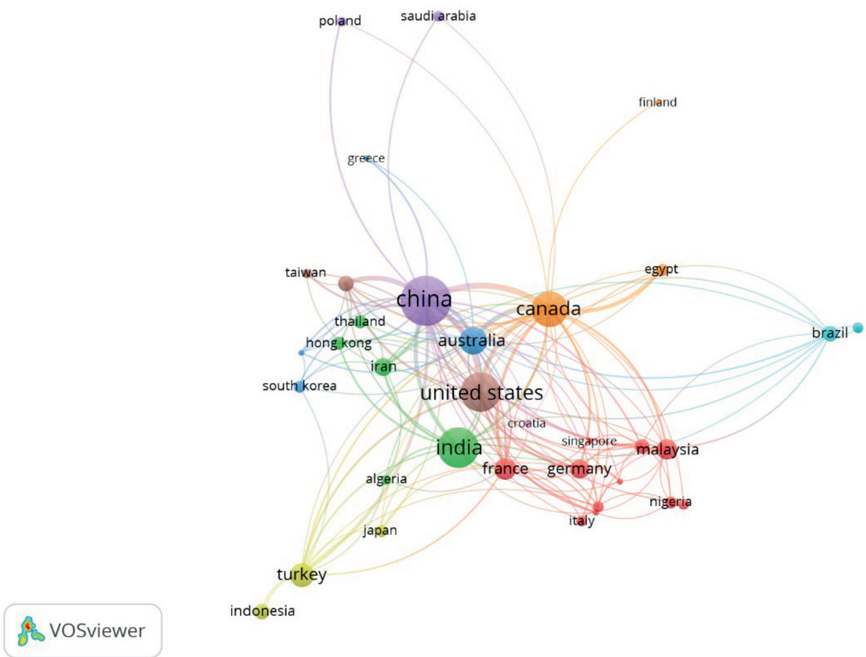

Fig. 3. Collaboration network strength between the countries.

Table 1. The institute network of landfill liner composite material-related publications.

Rank	Affilliation	Countries	Total Citation	Total Document	Networking Link
1	Queen's University	Canada	338	7	736
2	Univ. of Wisconsin	United States	163	4	272
3	Tsinghua University	China	78	2	319
4	Zhejiang University	China	66	5	880
5	Middle East Technical University	Turkey	65	3	65
6	University of California-San Diego	United States	60	2	267
7	Univ. of Virginia	United States	60	2	210
8	Tongji University	China	57	5	1031
9	Hohai University	China	56	4	306
10	Indian Institute of Technology	India	50	3	84

occupying the top position as the institute with the most citations, at 338. A total of 163 citations were obtained by the second-ranked institution: the University of Wisconsin in the United States; third place was Tsinghua University (78 citations) in China.

Citation and H-Index Analysis of Landfill Liner Composite Material-Related Publications

The number of citations indicates the most referenced authors. Additionally, according to Tahamtan et al. [47], citations can act as a parameter to indicate the quality of published articles. The articles in Geotextiles and Geomembranes received the most citations, 535. Ranked second was the Journal of Geotechnical and Geoenvironmental Engineering, with 458 citations. However, journals that ranked first for the most citations did not necessarily have the highest H-index. According to Díaz et al. [48], the H-index reflects reliable and authentic achievement. In other words, the H-index can be used as a parameter of journal quality. The Journal of Cleaner Production had the highest H-index of 200. This implies that the achievement of Geotextile and Geomembrane publication (H-index = 85) is still below the Journal of Cleaner Production.

Table 2 lists of the 10 most cited and productive authors who contributed to research on landfill liner composite materials. Rowe and Benson ranked first and second, respectively, with the most publications and the most influence. Both authors wrote similar publications on the GCL and received multiple citations. This finding implied that many authors are interested in GCL. However, comparing the data tabulated in Table 2, the third position and below are occupied by different authors in terms of the most productive and the most influential. For example, Bradshaw was the fourth most influential writer with 185 citations, but Xie was the most prolific, with 11 publications. The results

Table 2. Most cited and productive author of landfill liner composite material-related publications.

Rank	Most Cited		Most Productive	
	Author	Cited	Author	Publications
1	Rowe R.K	679	Rowe R.K	25
2	Benson C.H	331	Benson C.H	14
3	Brachman R.W.I	200	Xie H	11
4	Bradshaw S.I	185	Bouzza A	8
5	Xie H	163	Stark T.D	8
6	Take W.A	130	Feng S.J	8
7	Fox P.J	128	Touze-foltz N	8
8	Edil T.B	119	Rayhani M.T	7
9	Chen Y	101	Mukherjee K	7
10	Kerry Rowe	86	Brachman R.W.I	6

showed that the most productive authors are not always the most influential.

The Keywords Analysis of Research Hotspots on Landfill Liner Composite Material Study

From a total of 358 publications, we obtained 3066 keywords. The purpose of keyword analysis is to find indicators that match the trend and can be used for indication of future research trends [37]. We analyzed the obtained data using VOSviewer by identifying the 142 words that reached the minimum of 7 occurrences. We excluded unrelated terms, such as country and article type. We obtained the keywords ''landfill,'' "geosynthetic," "liner," "geomembrane," "GCL," "clay liner," "hydraulic conductivity," "bentonite," "leachate treatment," and "soil'." The highest number of occurrences was 221, for at least 69 keywords. These keywords reflected the topics most discussed by the author. Li et al. [49] stated that co-occurrence keywords are effective at indicating hotspots, providing additional information for scientific research.

Fig. 4 shows the keyword network of landfill liner composite material related publications, where the larger the node size, the higher the occurrence frequency and importance of the word. The largest nodes are for the keywords ''landfill,'' ''geosynthetic,'' ''liner,'' and ''geomembranes." This visualization shows that the authors paid considerable attention to landfill liner materials composed of geosynthetic and GMs materials. In comparison, the distance between nodes reflects the strength of a relationship. The shorter the distance, the stronger is the relationship, and vice versa. In addition, the line that appears between two nodes shows how often the two words appear together [50].

Fig. 4 shows the division of the keywords into five clusters: yellow, purple, red, blue, and green. The color difference in VOSviewer visualizations indicates that the division of the clusters according to the dominant topic. Cluster 1 (yellow) consists of 28 items and is dominated by issues regarding the tests conducted to determine the feasibility of making landfill liners, such as desiccation, shear strength, and compression testing. Cluster 2 consists of 23 items and is marked in purple. This cluster is dominated by studies on clay liners, particularly GCLs. In Cluster 3, in red, the authors focused more on discussing leachate, alternative management of other processing methods, and the impact of leachate on the environment. The dominance of these keywords slightly resembles that of Cluster 4, in blue, regarding the effects of contamination from leachate. However, Cluster 4 is dominated by CCL, which has the largest node. The last observed green cluster is a group that discusses linear building materials in bentonite, fly ash, and sand. In addition, we found that the dominant topic regarded geotechnical properties and the permeability of the constituent materials of the liner.

Content Analysis of the Top 5 Most Influential Articles Landfill Liner Composite Material Study

Table 3 presents the ten most cited, and therefore influential, publications related to landfill liner composite materials. The content includes a range of materials used to fabricated landfill liners, dominated by GCLs and GMs. For example, the topic of publication 1 is the long-term performance of leakage GMs and GCLs. GCL is widely used as a hydraulic conductivity barrier in landfills to minimize leachate

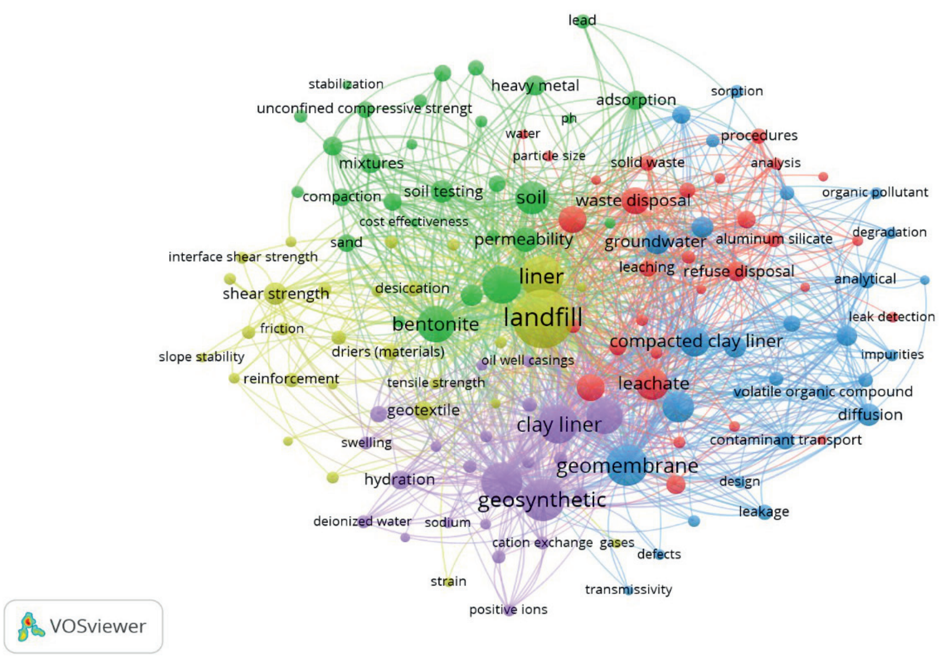

Fig. 4. Keywords co-occurrence network of landfill liner composite material-related publications.

Table 3. Content analysis of the top 5 most cited publications.

Rank	Cited	Author	Title	Aim	Method	Data or Result	Conclusion
1	183	Rowe [51]	Short- and long-term leakage through composites	To investigate the factors affecting the long-term performance of the leakage of geomembrane composite liner (GM) clay liner (CL) with emphasis on geosynthetic clay (GCL) liner.	Calculation of leakage through clay liners, composite liners, composite liners with wrinkles (Darcy's law, Interface transmissivity, Queen's University Environmental Liner Test Site /QUELTS, low-altitude aerial photogrammetric system)	GM single liner for landfill application obtained the following results: 0.3 m = 250 to 500 lphd 5 m = 1000 to 2000 lphd For a single clay liner as part of the primary liner in a double liner system, the leakages assuming typical design hydraulic conductivities	Leakage through composite coatings with geosynthetic clay liner (GCL) was much less than composite liners with compacted clay liner (CCL). The long-term performance of composite liners can run very well if maintenance is carried out, significantly if the temperature exceeds 35ºC.
2	81	Ple and Lê [52]	Effect of polypropylene fiber-reinforcement on the mechanical behavior of silty clay	To investigate the mechanical performance of a mixture of clayey soil and polypropylene fiber reinforcement as a barrier in landfill	Experimental test (proctor, compression, direct tensile test)	The value of Young's modulus increases and gives a stiff effect. The value of hydraulic conductivity increases with the addition of fiber, 0.3% - 0.6% fiber content maintains the value of hydraulic conductivity between 8 x10^{-10}m/s to 2.06 x $^{10-9}$ m/s. The increase in strength can reach about 20% under confinement, and from 0.6%, the fiber can increase the strength limit value up to 100%.	The addition of fiber to the polypropylene composite on clayey soil can improve its mechanical performance because the potential for cracking is reduced.
3	77	Rowe et al. [53]	Field study of wrinkles in a geomembrane at a composite test site	To investigate the factors influencing the formation of wrinkles and their most extended hydraulic features in composite liner geomembranes	A low-altitude aerial photogrammetry system, QUELTS	An area of 0.15 ha forms a wrinkle along 1500 m. The slope of about 2000 m creates a wrinkle of 0.17 ha. The total area of 22% causes the crease length to be around 1350 m, while the current 29% is 1950 m.	The area of the geomembrane affects the formation and length of the connected wrinkles. Influenced by the day and year, especially the difference in seasons.
4	68	Rowe [54]	Performance of GCLS in liner for landfill and mining applications	To examine the construction factors (moisture content, soil grain size, normal pressure, etc.) that affect the performance of geosynthetic clay liners (GCLs) composites as landfill liners.	Theoretical study	Factors that can affect GCL performance include the characteristics and interactions of the bentonite used, the characteristics of the geotextile and geofilm used, the moisture content and pressure of the GCL (>90% standard Proctor density).	GCL is more susceptible to low stress and cracking due to wet-dry cycles. Especially in landfills with temperatures exceeding 40 °C, which have more potential for leakage and diffusion.
5	64	Wu et al. [18]	Feasibility study on the application of coal gangue as liner material	To investigate the feasibility performance of coal gangue in terms of hydraulic conductivity, leaching characteristics, and sorption capacity towards heavy metals as landfill liners	Permeability test, batch sorption test, Sorption kinetics analysis, Equilibrium isothermal sorption analysis, Thermodynamics analysis, and Toxicity characteristic leaching experiment	Cavity ratio = < 0.60, hydraulic conductivity = < 10^{-7} m/s (meets requirements for monolayer landfill liners)	Based on the results obtained from the hydraulic conductivity, leaching behavior, and sorption characteristics tests that have been carried out, coal gangue can be applied as a building material for landfill liners.

infiltration [55]. In addition, according to Bouazza et al. [56] Geosynthetics have a function in waterproofing applications.

In publication 1, written by Rowe [51], the aim was to investigate the factors affect the long-term leakage of liners. The author considered a composite GM and CL, emphasizing a GCL and calculated the leakage. The test results showed fewer leaks in the liner coated with GCL. The reason for the lower leakage rate role of GCL as a leachate migration barrier is its good interfacial transmissivity. In addition, the liner can perform well in the long term if maintenance is performed, especially if the temperature exceeds 35ºC. As temperature increased, the potential for the GCL to dry and crack also increased. The data showed that landfill liners at 30-40ºC, coupled with a 1.5 mm GM HDPE, can last for thousands of years. Therefore, the authors suggested further research focusing on the long-term temperature when GM and GCL are used as a landfill liner; other parameters, including the design, material, method of operation, cooling of the secondary layer, tensile strain, and drying, should be considered.

Publication 3 written by Rowe et al. [53], describes GMs composites and the factors influencing liner wrinkle formation and their most extended hydraulic features in composite linear GMs. The area and duration were found to affect the appearance and length of the wrinkles on the GM. The formed wrinkles are longer if the site is larger. A total area of 22% caused the crease length to be approximately 1350 m, whereas 29% resulted in a crease length of approximately is 1950 m. However, the maximum wrinkle length can be determined in a given area to anticipate area restrictions. Wrinkles are affected by the day and time year, and especially by seasonal differences. Climate change causes differences in GM temperature, where wrinkling occurs when temperature increases. Summer and spring can cause long wrinkles, whereas winter and early spring (GM temperatures below 30ºC) minimize wrinkling.

The subsequent publication 4 discuss GCL but theoretical studies. Rowe [54] reviewed studies on the performance of GCLS in liners, especially construction factors such as moisture content and pressure. The author concluded that GCLs are more susceptible to low stress and cracking due to wet-dry cycles, especially in landfills with temperatures exceeding 40ºC, which have higher leakage and diffusion potential. Rowe [52] also found that a good landfill liner should be used at temperatures less than 40ºC. Moreover, above 35ºC, the liner system should be upgraded to reduce drying, which can cause cracks and leaks. Another method involves monitoring the acceptable moisture content, avoiding leachate recirculation, and disposing of combustion ash, which can increase the temperature and provide insulation as a liner temperature controller. The addition of a graded filter layer between the GCL and leak detection system can reduce the liner temperature. The addition also prevents GCL hydration and the internal erosion of the bentonite. The author also mentioned that interfacial transmissivity plays an essential role, such as in hydraulic conductivity. Therefore, proper selection of the design, material, and construction is required to increase the transmissivity of the GCL and avoid leakage.

Publications 2 and 5 cover materials different from those considered in the other three publications. Ple and Lê [52], publication 2, conducted an experimental test (proctor, compression, and direct tensile tests) to investigate the mechanical performance of a mixture of clayey soil and polypropylene fiber as a reinforcement barrier in a landfill. The results showed that adding fiber to the polypropylene composite on clayey soil improved its mechanical performance because the risk of cracking decreased. Adding fiber helped clay withstand overload, reducing cracking and breakage. A differential decrease also occurred, increasing the stability of the landfill. In addition, the hydraulic conductivity increased with the addition of fiber but had to be maintained at an acceptable dose at the site. The use of fiber is technically feasible, but should be tested in the future under actual geotechnical project conditions.

Wu et al. [57], in publication 5, conducted performance feasibility studies with the application of coal gangue materials. They found coal waste is a possible alternative to landfill liners for conserving natural resources, improving recycling old materials, and minimizing the use new materials. Based on the results of the hydraulic conductivity, leaching behavior, and sorption characteristic tests, they found coal gangue can be used as a building material for landfill liners. The hydraulic conductivity value was not greater than that of the standard monolayer liner (0.60). In addition, the Zn^{2+} and Pb^{2+} absorption capacity was large, so the leachate concentration was lower and met the applicable standards. The authors recommended further research on other heavy metals because the Zn^{2+} and Pb^{2+} absorption decreases in the presence of other heavy metals.

From the most influential articles analyzed, we found that the GCL landfill liner was the most discussed. Other materials, such as waste (coal gangue) and fibers, were considered in several articles. However, they have not attracted considerable attention from scientists. These topics may be discussed more often in the future because their impact is good for environmental sustainability and the economy. According to Qiang et al. [58] the application of a mixture of fiber materials to clay and concrete in recent years aims to increase shear strength and resistance to cracking. However, fly ash waste has chemical and geotechnical properties that play an important role in landfill operations related to; location, slope stability; leachate seepage, and reduction in landfill [59]. In addition, most of the limitations of the prior studies are related to the scale; therefore, further research must be conducted at the real-world or field scale.

Conclusions

The evolution of research on landfill liner composite materials has fluctuated in volume but has shown a tendency to increase, receiving considerable interest from researchers from 2011 to 2021. The 358 publications were published in 145 different journals, where Geotextiles and Geomembranes ranked first with 26 publications. Based on the collaboration and productivity analysis, China and Canada had the strongest relationship, as indicated by the thickness of the link that connected their nodes. China was the most productive country, with 83 publications, followed by India (57 publications) and the United States (53 publications). Queen's University was the most prolific and influential affiliate, with 338 citations and 7 publications.

The results of citation analysis indicated the most referenced journals, where the H-index indicates journal quality. The journal that ranks first in the number citations does not necessarily have the highest H-index. Geotextiles and Geomembranes was the most cited journal (535 citations), whereas the Journal of Cleaner Production had the highest H-index of 200. Rowe and Benson were the first- and second-most-cited authors, respectively, and wrote similar publications regarding GCLs.

The analysis of 142 keywords from 358 publications showed trends in the keywords ''landfill," "geosynthetic," "liner," "geomembrane," "GCL," "clay liner," "hydraulic conductivity," "bentonite," "leachate treatment," and "soil'' as the most frequent in the field. The density analysis produced similar results, as the authors focused on landfill liner materials composed of geosynthetic and geomembrane materials. In addition, we divided the keywords into five clusters with different research hotspots. We also analyzed article content as a complement to the in-depth analysis of this research topic. From the 10 most cited articles, the content describes the wide range of materials used or considered for landfill liners, being dominated by GCLs and GMs with varying specifications. We found that other liner materials, such as waste (coal gangue) and fiber, were considered in several articles but they did not have much effect on the field, but they have attracted research attention, so they have the potential to be studied more in the future. The positive impact of reusing unused materials was also considered.

Although the findings presented here provide results of a bibliometric analysis of the field of landfill liner composite materials, the study has several limitations. We only included data downloaded from the Scopus database, and future researchers may consider using other databases such as the Web of Science to compare the data. Furthermore, we only used quantitative analysis in content analysis, so in further studies, text can be mined to obtain more in-depth results. Finally, we only reviewed the data from 2011 to 2021. The data from 2001 to 2021 should be considered to identify longer-term trends in the field.

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Conflict of Interest

The authors declare no conflict of interest.

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