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Review Article

Global trends of landfill leachate treatment research: A bibliometric analysis during 2000-2020

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Abstract
Landfill leachate is heavily contaminated and consists of high amount of organic compounds, toxic gases, inorganic salts, halogenated hydrocarbons, and heavy metals that exerts a serious threat to public health and the environment. Therefore it requires treatment before direct discharge into water bodies. Although landfill leachate treatment has been studied by many researchers, lacking comprehensive review in this area can be considerable. This paper aims to assess the trend of landfill leachate treatment research and to show the related hotspots through conducting a bibliometric analysis, based on 3523 publications from Web of Science during 2000-2020. Various significant aspects including document type, publications growth trends, key countries/territories, subject categories, major journals, and keywords co-occurrence, were all systematically analyzed in this paper. Also, VOS viewer has been employed to evaluate the collaboration of countries/territories and keywords. Based on the results, the growing number of publications related to landfill leachate treatment over the last 20 years, demonstrate significant growth trends of the research. According to the subject category analysis, the most dominant categories were Environmental Sciences and Environmental Engineering with more than 60% contribution. "Waste Management" is the most productive journal followed by "Journal of Hazardous Materials", "Desalination and Water treatment", and "Water Science and Technology". China is the leading country in contribution to the total number of publications followed by the USA and Malaysia. Moreover, to identify the pioneer countries, keyword clustering analysis was conducted and it demonstrated that the number of landfill leachate-related publications have significantly increased during the studied period.
Keywords: Landfill, Leachate, Waste management, Research trend, Bibliometric analysis

Introduction

Population growth and the rise in living standards, have led to uncontrolled material consumption resulting in the generation of huge quantities of solid waste (Kurtoğlu Akkaya and Bilgili, 2020). Compared to composting and incineration, landfilling is the most common method for waste disposal due to its inexpensive capital cost and easy operation (Ribera-Pi et al., 2020). With time, a variety of different reactions, resulting from percolation of rainfall, moisture content, runoff and groundwater inflow, takes place in landfills and consequently,

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leads to the production of gases such as CH_4, CO_2, etc., and contaminated liquid named landfill leachate (Apaydin and Özkan, 2020; Tulun, 2020). Landfill leachate is a complex combination of pollutants, typically consisting high concentrations of ammoniacal-nitrogen (NH_3-N), inorganic salts, xenobiotic compounds (volatile, hydrophobic, aromatic, and aliphatic organic substances, to name but a few), recalcitrant matters, high chemical oxygen demand (COD), biological oxygen demand (BOD), and heavy metals. Depending on regional weather conditions (rainfall and temperature), solid waste composition, age, and origin of the landfill and landfill operation, the composition of landfill leachate may remarkably vary (de Oliveira et al., 2019; Ukundimana et al., 2020).

Soil and groundwater surrounded by landfill sites could become contaminated due to infiltration of raw leachate; therefore the leachate exerts a serious threat to public health and the environment (Bakhshoodeh et al., 2020; Yu et al., 2020). As the concentration and composition of the leachate are determined, it will be necessary to implement treatment processes - prior to its discharge- in order to prevent the potential contamination caused by landfill leachate (De et al., 2019; Tałałaj et al., 2019).

Various physico-chemical and biological processes have been applied for landfill leachate treatment (Djeffal et al., 2019) including coagulation-flocculation, air stripping, adsorption, advanced oxidation process, membrane filtration, activated sludge such as membrane bioreactor to mention but a few. Coagulation-flocculation is based on the neutralization of electrical charges that make colloidal particles close to each other and form flocs (Berradi et al., 2014). The process of air stripping is transferring a liquid consisting of free-form ammonia to a gas phase, when a forced air stream is in contact with the liquid (dos Santos et al., 2020). Adsorption occurs when the surface of a solid is concentrated with a solute as a result of being in contact with the solution (San-Pedro et al., 2020). Advanced oxidation process is the oxidation of complex organic compounds into end products that can be achieved by the generation of hydroxyl radicals that react rapidly with organic constituents (Pieus Thanikkal and Pooppana Antony, 2021). Over the last two decades, the application of membrane process in leachate treatment which its separation efficiency depends on the type of membrane, type and molecular size of contaminants, and the operational pressure, has attracted much attention (de Almeida et al., 2020). Membrane bioreactor is the integration of filtration and activated sludge in which separation of solid from liquid is carried out in a filtration unit using a membrane system (Pieus Thanikkal and Pooppana Antony, 2021). To meet the strict standard requirements and by taking the aforementioned methods into account, the most efficacious method for treating landfill leachate should be selected (Chen et al., 2020).

Opting for leachate treatment techniques to reduce environmental impacts is among the issues that need to be addressed. It is difficult to make general recommendations due to the complexity of the composition of the leachate. Above all, an appropriate treatment technique should be effective, easy to operate and inexpensive (in terms of investment and especially in operation and maintenance cost), and environmentally friendly so as to consume less energy and produce less excess sludge (Omran et al., 2021).

Numerous studies have been published on the leachate treatment. However, few attempts have been made to summarize the studies and to present a comprehensive review of leachate treatment and to the best of the authors' knowledge, there have been no bibliometric papers over the past 20 years.

Bibliometric analysis, is a useful tool used to quantitatively (in terms of annual outputs, mainstream journals, leading countries, and institutions) and statistically (in terms of hotspots and future research orientations) reveal global trends in specific fields of research (Wang et al., 2016; Zhi and Ji, 2012).

Accordingly, this paper aimed to comprehensively and systematically analyze the global research trends in the leachate treatment field from 2000 to 2020, employing bibliometric methods. Various aspects pertaining to subject categories, countries, journals, and keywords were assessed.

Methodology and data

The literature data was collected on November 8, 2020. Based on De Tre et al. (2014), since the source database Web of Science Core Collection, indexes high-quality documents, it was chosen among other famous databases e.g., Scopus and Google Scholar, and the publications were extracted only from 2000 to 2020 in this study. The Web of Science (WoS) is the most frequently used database which is a reliable search engine of scientific publications (Yang et al., 2013). The term "landfill leachate treatment" in abstracts, titles, and keywords, was selected to conduct the search within topic. Moreover, different combinations of keywords produced the same results.

Among 29 subject areas, environmental science, environmental engineering, chemical engineering and water resources had the highest number of publications during 2000-2020. It is worth mentioning that numerous categories such as zoology, forestry, and hematology to mention but a few, have been excluded since these subjects were not related to this study. The total number of publications (3523) included 87.4% journal articles (3082), 6.04% proceeding papers (213), 5.33% reviews (188) and 1.13% early access (40) during 2000–2020. As shown in Figure 1, the largest portion is dedicated to articles and proceeding papers respectively, that sum up to more than 93%.

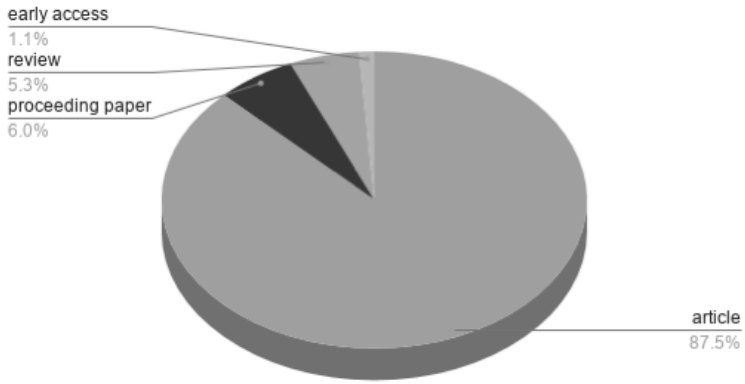

Figure. 1 Publication categories from 2000 to 2020

With regard to the language, more than 97% of publications were in English, whereas, 0.9% of publications were in Portuguese and the sum of the other languages was less than 2%. This paper was referenced using Mendeley (ELSEVIER) and the presented charts were created by Google Sheets and GraphPad prism.

Results and discussions

Publication growth trend analysis

As shown in figure 2, the number of related publications and the annual number of citations has progressed incrementally over the last 20 years. There were only 32 publications in 2000 and the number of publications reached a peak in 2021 which was the most productive year

regarding the number of publications with 364 publications. This trend shows a notable amount of attention to the subject of "landfill leachate treatment" by the researchers recently.

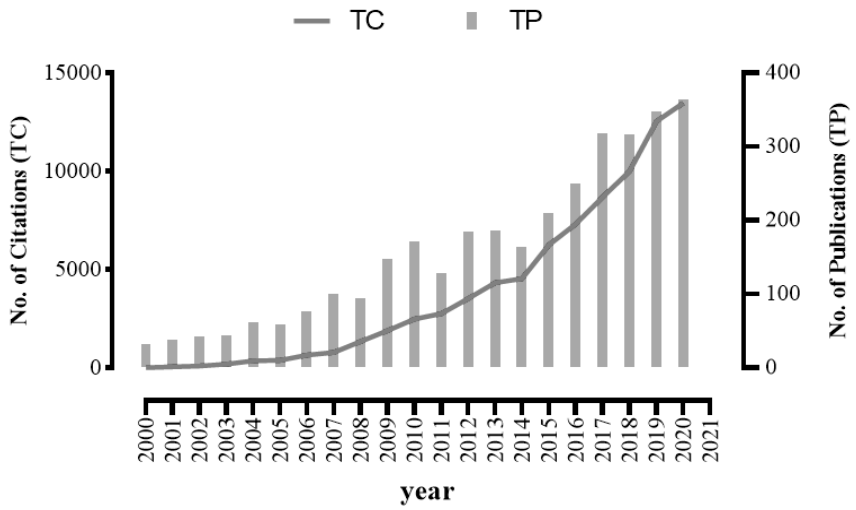

Figure. 2 Number of selected publications and citations

Such boom might be related to more than just scientific interest; specifically, it's far in line with the stricter enforcement of environmental guidelines and landfill leachate treatment policies, which have become restrictive due to some catastrophic occasions. For instance, "Teshima Island" in Japan that is considered as one of the most awful environmental disasters.

Landfill Directive, Water Framework Directive, Waste Framework Directive, Municipal Wastewater Treatment Directive, and Part 258 of Federal Legislation code for landfills are one of the most influential laws governing landfilling and leachate management. These guidelines have had a major effect on leachate management policies, particularly its collection and discharge (US EPA, 2011).

According to statistics, the amount of solid waste generated each year in China increases every five years (Huang et al., 2018). In this regard, the "Law of the People's Republic of China on the Prevention and Control of Environmental Pollution by Solid Waste" is one of the important laws in the context of pollution caused by waste mainly through leachate from landfills, forcing local authorities to design specific measures.

Subject categories

WoS presented 96 different disciplines and the top Web of Science subject categories in terms of the number of publications are shown in figure 3. Among the most significant categories, the prominence of Environmental science and Environmental Engineering with 61% was noticeable. The next category to be the most dominant was Water Resources by 12%, Chemical Engineering by 11.8%, and the rest was about 15%. As can be concluded from figure 3, environmental impacts of landfill leachate have attracted more attention due to the fact that they are able to prevent both health issues and environmental risks.

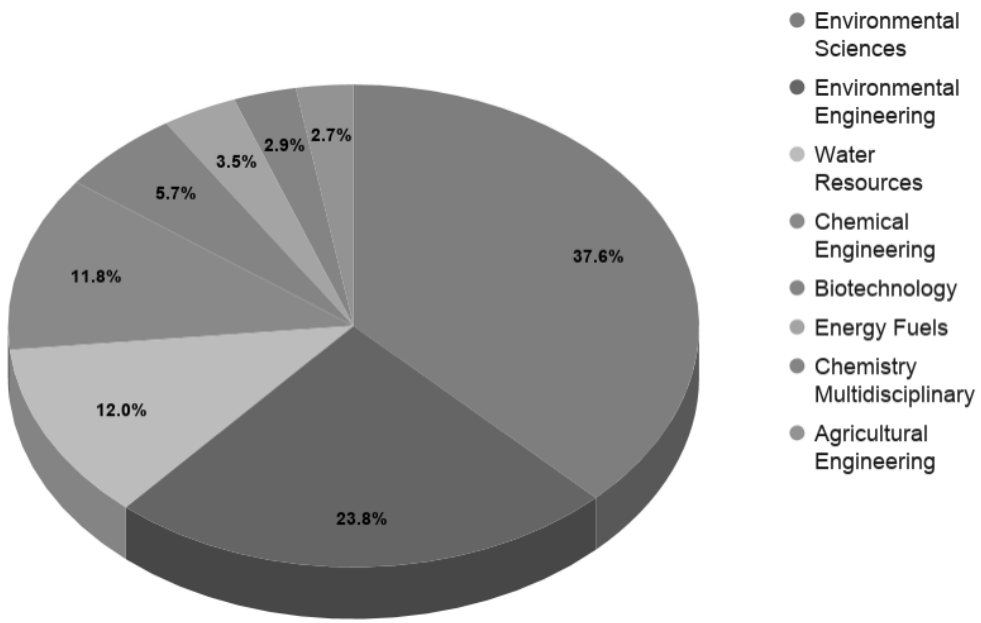

Figure. 3 Top 6 WoS categories in terms of number of publications

Countries analysis

Figure 4 shows the top 15 productive countries in terms of the total number of publications within the dataset, from 2000 to 2020. There were seven Asian countries, five European countries, two North American countries, and one South American country. In particular, China with 893 articles (26.8%) had the highest number of publications. Considering the characteristics of municipal solid waste in China which makes it unsuitable for incineration and the environmental impacts of heavy metals in composting that deteriorates its quality (De et al., 2019; Ji et al., 2016; Wei et al., 2000) , sanitary landfilling has attracted more attentions and that could be one of the salient reasons for the proliferation of China. Another reason, capable of explaining this result, is the fact that there is already a plethora of leachate treatment facilities in China. This, in turn, encourages Chinese researchers to investigate leachate treatment.

Also, China's superiority here might be attributed to the Chinese government's strong support in water monitoring and cleaning up contaminated water sources in recent years. Interestingly, some parts of China experience more severe water scarcity than some countries in the Middle East. Such scarcity has convinced the government to invest large sums in controlling water pollution through water pollution prevention and control measures. In addition, it is reported that the Chinese government has allocated an additional budget of US $1700 million for 20 heavily water-polluted cities (Sillanpää, 2018).

USA ranked as the second with 279 articles (8.4%) followed by Malaysia (202, 6%), Brazil (188, 5.6%), Turkey (184, 5.5%), Italy (163, 4.893%), Spain (161, 4.83%), Poland (154, 4.6%), India (145, 4.3%), Canada (141, 4.2%), Iran (138, 4.1%), Japan (106, 3.1%), Australia (86, 2.5%), South Korea (82, 2.4%), and England (74, 2.2%). According to Figure 4, the number of developed countries such as Canada, Australia, and Japan in this category was more than developing countries such as Iran, China, and Brazil.

Since the establishment of the National Policy on Solid Waste in Brazil, efforts have been made to improve landfill conditions. Such efforts also include landfill leachate management, for example through treatment and recirculation (Costa et al., 2019). Concerns like these may have prompted Brazilian institutes to devote more budgets to landfill leachate treatment studies.

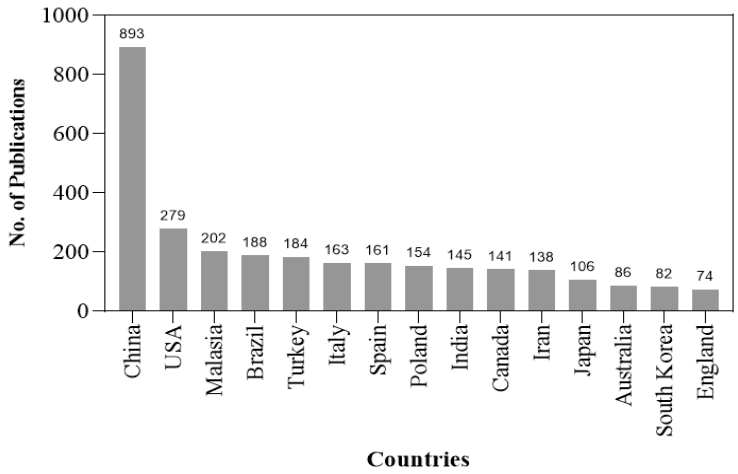

Figure. 4 Top 15 productive countries within the WoS

Figure 5 illustrates the co-authorship network analysis between the top 15 productive countries in landfill leachate treatment studies. Among these countries, some are located at the center of the network (such as China), which implies that they tend to cooperate with other countries. On the other hand, some countries like Iran are marginally located, meaning their research efforts are more isolated. In this Figure, each node represents a country, and the lines between the two nodes (country) show their collaboration. The number of times the two countries have worked together is called the strength of the relationship. The total linking strength of a country is the total number of times it has cooperated with other countries.

As shown in Figure 5, China is the first ranked regarding the number of publications and collaborations with a total link strength of 141, since China is the world's second-largest sending country of international students. The second and third ranks of the international collaborations are for the USA and Australia with 128 and 57 total link strength, respectively. Furthermore, Poland, Turkey, and Brazil are the lowest collaborative countries, which can be deduced that economic development plays an important role in the collaboration between countries.

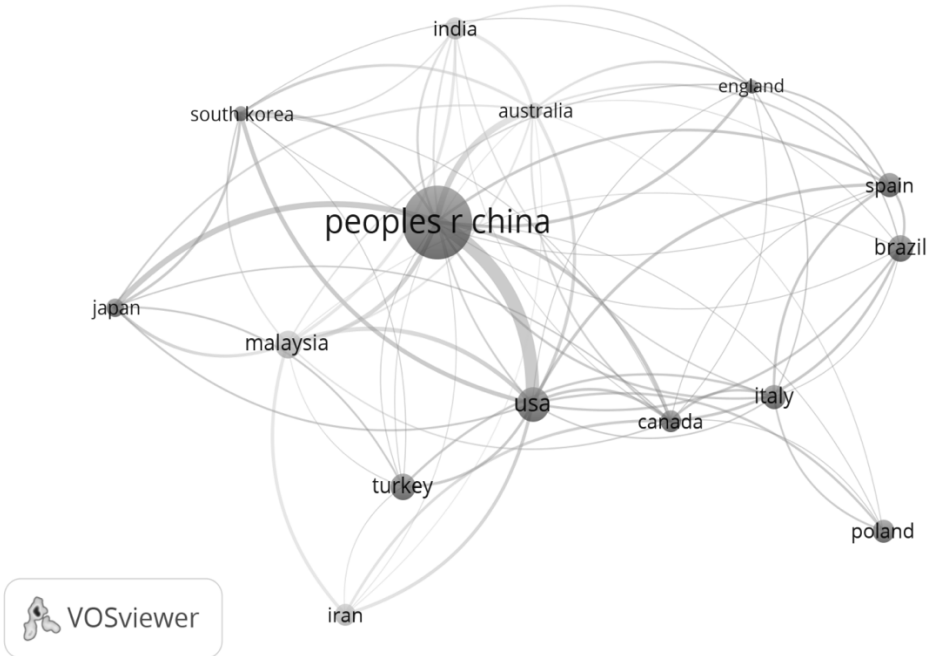

Figure. 5 Co-authorship network analysis between the top 15 productive countries

Figure 6 presents the annual trends of publications related to the five productive countries in landfill leachate treatment from 2000 to 2020. Although the number of publications has fluctuated, the overall trend has been positive during this period. As can be seen, from 2002 to 2004, the USA took the first rank and the publications were mainly focused on single treatment methods. China's publications dropped sharply in 2003 since the researchers focused on employing other methods of waste management such as incineration and composting. Municipal solid waste in China has high moisture content and low heating value, making the application of incineration difficult (Wang and Nie, 2001). Furthermore, waste collection without separation results in low-quality compost (Ji et al., 2016). Therefore, in 2006, the number of publications in landfill leachate treatment was more than the USA for the first time and has increased dramatically from 7 in 2006 to 140 in 2020 consolidating the fact that China was a pioneer in the selected topic; moreover, the publications were mainly focused on combined treatment methods such as combination of coagulation and ozonation (Xiang et al., 2020), coupling electrocoagulation and electro-oxidation (Soomro et al., 2020), and integration of sequencing batch reactor and electro-Fenton oxidation process (Ai et al., 2019). The number of publications of the other countries varies and doesn't follow a specific pattern. Even more detailed analysis of the less-productive countries did not reveal a significant pattern about the nature of their publication. Thwarting any potential attempt to further discuss these countries.

In conclusion, in order to meet discharge requirements, landfill leachate treatment has been widely explored by researchers in different countries during 2000-2020.

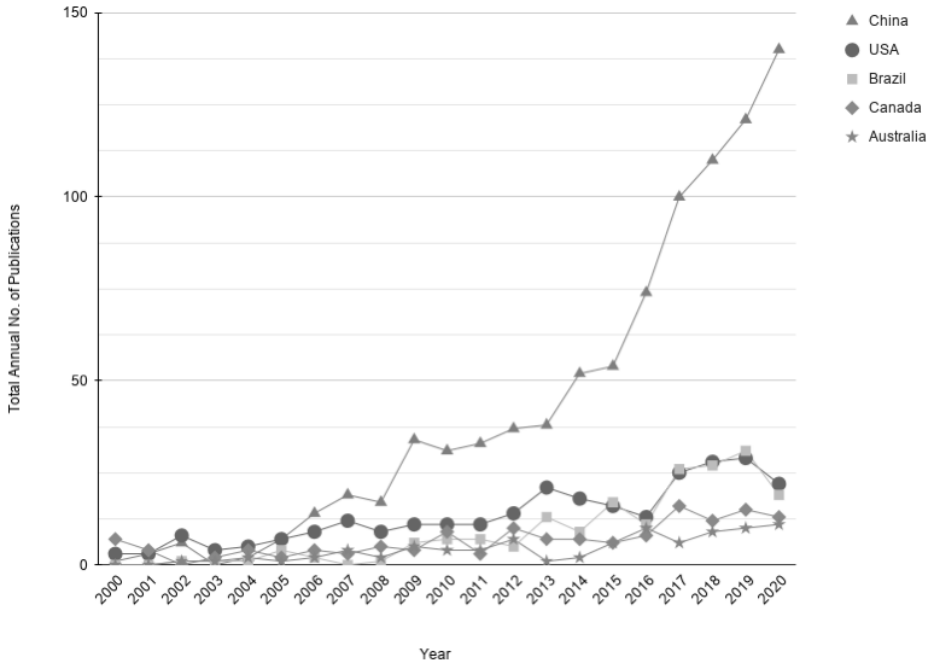

Figure. 6 Growth trends of total publications of the 5 productive countries

Journal analysis

The 3523 publications related to landfill leachate treatment were from 355 Journals. But, only 41 Journals with more than 15 publications were selected. The Journal impact factor (JIF) is defined as the number of citations received in a year in which the articles are published in that journal within the two preceding years (Miranda and Garcia-Carpintero, 2019). JIF is one of the well-known indicators widely used to illustrate the quality of research publications (Bornmann et al., 2012). Moreover, the Quartile Rankings (QRs) of journals provide

beneficial information in terms of citation and ranking and are determined based on the subject categories that the journal incorporates and its IF in those categories (Asan and Aslan, 2020; Miranda and Garcia-Carpintero, 2019). According to Table 1 presenting the 10 most productive journals with the impact factor in the year 2020 and quartile in categories, "Journal of Waste Management" had the highest number of publications (249), followed by "Journal of Hazardous Materials" (167), "Desalination and Water treatment" (162), and "Water Science and Technology" (153). It is worth mentioning that more than half of the journals in the table have IFs higher than 3. Also, 8 out of them are Q_1 and Q_2 and just 2 out of them are Q_3 in the ranking, it can be deduced that landfill leachate treatment has been attracting a lot of attention from high-level journals.

Table 1. Top 10 productive Journals within the dataset during 2000-2020

Rank	Journal	No. of Publications	I.F. 2020	Quartile in Category
1	Waste Management	249	5.9	Q_1
2	Journal of Hazardous Materials	167	8	Q_1
3	Desalination and Water treatment	162	1.3	Q_3
4	Water Science and Technology	153	1.5	Q_3
5	Bioresource Technology	138	6.9	Q_1
6	Chemosphere	123	5.3	Q_1
7	Environmental Technology	115	1.8	Q_2
8	Environmental Science and Pollution Research	107	3	Q_1
9	Chemical Engineering Journal	99	10.6	Q_1
10	Science of the Total Environment	96	5.9	Q_1

Keyword co-occurrence network analysis

Keywords are one of the primary means for researchers to indicate the content of a study. Keyword network analysis is a method to discover directions and well-known topics that provide useful information about research trends and has been proved to be crucial for monitoring the development of research topics and programs (Chen et al., 2016; Gao et al., 2017; Li et al., 2008). Social network analysis was employed to find out publications related to the topic by using keywords. The minimum number of keywords was set to 15. Hence, among 9875 keywords, 371 met the threshold. Some keywords have been revised since they expressed same meaning with the different forms. For example:

- From UASB, upflow anaerobic sludge blanket, and UASB reactor, upflow anaerobic sludge blanket was selected.
- From MSW, municipal solid waste, and municipal solid-waste, municipal solid waste was selected.
- From H_2O_2, hydrogen peroxide, and hydrogen- peroxide, hydrogen peroxide was selected.
- From sequencing batch reactor, and SBR, sequencing batch reactor was selected.

Overall, the dataset was manually reviewed to merge these items. This is an important issue because if it remains unmerged it can significantly damage the quality of keyword analysis because VOS viewer connects nodes and establishes connections based on co-occurrence of different keywords in the same article.

Networking maps and VOS Viewer were applied to analyze the co-occurrence of keywords (Van and Waltman, 2010) in Figure 7. Each curve indicates a co-occurrence

relationship between the two linked keywords, and each node indicates a keyword. As depicted in Figure 7, the keywords were divided into 5 clusters.

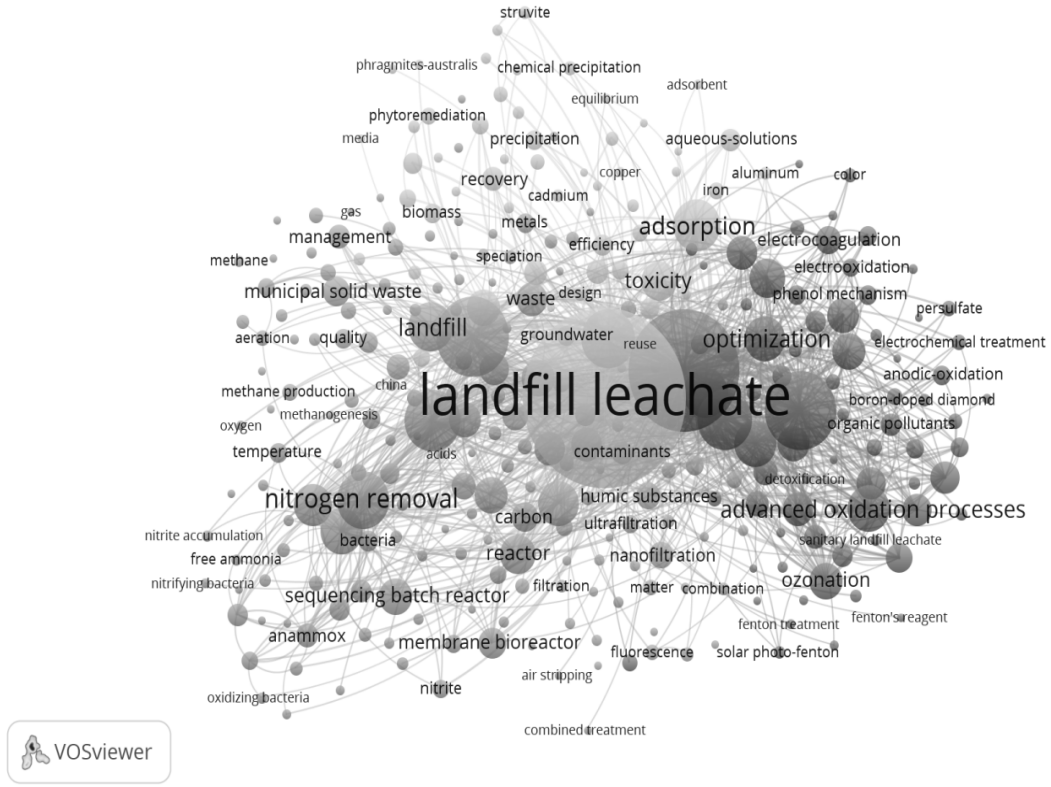

Figure. 7 Co-occurrence of keywords within the dataset

Table2 presents more detailed information about these clusters to specify the concentration of each cluster. Based on Table 2, it can be realized that most of the keywords are related to methods of landfill leachate treatment such as “biological treatment”, “adsorption”, and “nanofiltration”. Furthermore, “landfill leachate” (1725) in cluster 4, “removal” (937), “degradation” (470), and “oxidation” (308) in cluster 1, are the top fourth most occurred keywords and can be concluded that the issue of landfill leachate, decomposition, oxidation, and then removal of pollutants is of great importance. Nitrogen removal processes such as the Anammox process, nitrification-denitrification process, endogenous denitritation process, and nitritation-denitritation process, all are related to biological treatments since biological treatment of leachate is applied to remove nitrogen and organics (Miao et al., 2019). According to cluster 3,”nitrification” and “denitrification” resulting in “nitrogen removal” from leachate, are highly occurring keywords. Out of cluster 4 and 5 results, it can be understood that “toxicity” and “water” are other keywords with high occurrences due to the fact that leakage of leachate affects the surrounding environment especially the water bodies, because the leachate consists of high concentrations of toxic contents leading to its toxicity (Naveen et al., 2018).

Table 2. Clustering, colors and Keywords with the most occurrences

Cluster #	Color	3 top Keywords (occurrences)
1	Red	Removal(937), Degradation(470), Oxidation(308)
2	Green	Landfill(219), Biological Treatment(191), Waste(172)
3	Blue	Nitrogen Removal(283), Nitrification(201), Denitrification(178)
4	Yellow	Landfill Leachate(1725), Adsorption(246), Toxicity(162)
5	Purple	Water(297), Waste Water Treatment(123), Nanofiltration(90)

Conclusion

This bibliometric study has been carried out to provide a perspective on the research trends in landfill leachate treatment based on Web of Science database during the period 2000-2020. Document types, subject categories, countries/territories, productive sources, and keywords were some aspects that have been investigated in this study. The results revealed that landfill leachate treatment researches have progressed considerably during the studied period and the number of publications on the selected topic has increased drastically from 32 in 2000 to 364 in 2020. This growth is attributed to stricter legislation in recent years and more budgets devoted to pollution control. Since the advent of landfill leachate treatment studies, many different topics and research areas have been included in the literature.

A total of 3523 publications were published in 96 subject categories and the top 4 subject categories were Environmental Sciences, Environmental Engineering, Water Resources, and Chemical Engineering. In this paper, the collaboration between countries was mapped by VOS viewer software. In this evaluation, China attained a dominant position in landfill leachate treatment research by contributing the highest number of publications (893), followed by the USA and Malaysia ranking second and third with 279 and 202 articles, respectively. Journals of “Waste Management”, “Hazardous Materials”, “Desalination and Water treatment”, and “Water Science and Technology” published most articles on landfill leachate treatment in the last 20 years. According to the analysis of the keywords, “landfill leachate”, “removal”, “degradation”, “oxidation”, “water” and “nitrogen removal” were the most occurred keywords during 2000-2020.

Analysis of these publications and their bibliographic information and related citations has shown that Oxidation of the leachate is one of the hottest research areas, along with membrane and adsorption methods. The importance of nitrogen removal by treatment also emerges from bibliometric analysis, which makes sense because nitrogen removal does not occur naturally in landfills. In addition, it seems that the before-mentioned techniques are promising and recommended methods for landfill leachate treatment.

Therefore, the fact that the waste production rate is faster than the world’s population, makes waste management a major environmental problem worldwide. Moreover, to meet the environmental requirements regarding water bodies, the treatment of landfill leachate becomes an environmental concern.

To conclude, the outcomes of this paper could help researchers to have a better understanding of the current situation, overall progress, and the trends of landfill leachate treatment and prepare a base for future studies in this field.

Authors' contributions:
Mohammad Reza Sabour has contributed equally.
Shamimeh Babaei Khorzoughi has contributed equally.
Saman Moftakhari Anasori Movahed has contributed equally.

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