Global research trends in petrochemical wastewater treatment from 2000 to 2021

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Abstract

Petrochemical wastewater (PWW) is a huge industrial contaminant that generates a wide range of resistive and poisonous organic pollutants that harm animals and plants in natural water bodies when discharged untreated or partially treated. Therefore, it is vital to develop technologies that are simple, efficient, and profitable for the treatment of oily wastewater. Although, much study has been undertaken on the treatment of PWW, there hasn't been any recent work on bibliometrics analysis of global research trends on this issue. A bibliometric analysis will help current and future researchers figure out where the gaps are and how to fill them. The present study's focus is to examine the characteristics and trends of research on oily wastewater treatment with an emphasis on the treatment of PWW. This research was performed on five important aspects, including characterization of research publications; countries' performances and collaborations; an analysis of the best papers with the most citations; keyword analysis (including frequency distribution of the keyword analysis; the transformation of the keyword combination across time; and exploration of changes in rank over time); and journal analysis, according to the 2457 papers in the Science Citation Index Expanded using the Web of Science (WoS) database from 2000 to 2021. For further analysis, the contingency matrix, bump diagram, and inter-temporal network stream were employed.

Introduction

Oily wastewater (OWW) is wastewater that has been combined with oil in various quantities. Fats, hydrocarbons, and petroleum fractions such as diesel oil, gasoline, and kerosene may all be found in the oil mixed with water. Metal processing industries, dairy industries, restaurants, slaughterhouses, edible oil refineries, petrochemical industries, tannery industries, poultry processing industries, and other sectors all produce enormous amounts of oily wastewaters nowadays (Şana SUNGUR 2017; Kuyukina et al. 2020; Sanghamitra et al. 2021). Among all the types, the United States Environmental Protection Agency considers petrochemical wastewater (PWW) to be one of the most toxic and environmentally dangerous types (Adetunji and Olaniran 2021). Petrochemical products are now widely employed in a variety of applications, and excessive use of these items for a variety of purposes pollutes the environment (Cechinel et al. 2016). The petrochemical industry emits significant amounts of effluent, including harmful and stubborn organic pollutants such as BTEX (benzene, toluene, xylene, and ethylbenzene), sulfides, hydrocarbons, phenol, and heavy metals (El-Naas et al. 2014; Raza et al. 2019). Releasing petroleum refinery wastewater into the environment untreated or partially treated pollutes aquatic ecosystems, produces an unfavorable environment, costs a lot of money to clean up, and results in the loss of farmland and fish (Mustapha 2018). Regrettably, the United States' National Research Council reported in 2002 that 1.3 million tons of oil were discharged into the ocean each year from authorized sources (Ahmad et al. 2020).

As a result, it is critical to create simple, efficient, and cost-effective methods for removing oil spills and industrial organic solvents from oily effluent. There have been substantial investigations into three common procedures and their mixtures for dealing with PWW so far: physical treatment, chemical treatment, and biological treatment (all of which have been thoroughly explored) (Peng et al. 2018; Doshi et al. 2018).

The chemical techniques used to treat oily wastewater include flocculation, adsorption, and more recently, electrochemical technology (ET) (Han et al. 2019; Abuhasel et al. 2021). Chemical treatment introduces additional contamination, although biological treatment is unpredictable and slow (Lee et al. 2019; Dai et al. 2019). Common biological treatments may be categorized into aerobic treatment or anaerobic treatment methods. Anaerobic processes use much less energy due to the lack of aeration, have the potential to convert organic pollutants to methane gas, need fewer nutrients, and produce less sludge (Primasari et al.). Aerobic biological treatment is used to treat high-temperature, high-pollutant concentration wastewater due to its quick biodegradation kinetics (Kurian et al.). The most challenging aspect of developing a biological treatment system is ensuring that the system remains stable when subjected to high salinity and toxicity levels in the wastewater stream (Abuhasel et al. 2021).

Physical treatment, in particular, is more appealing for the treatment of oily wastewater because it allows for the collection of oil (water) in situ from water (oil) without secondary contamination, which is considered to be the most successful approach for treating oily wastewater (Wang et al. 2020; Zhan et al. 2020). Physical absorption is the most prevalent physical treatment approach, which uses absorption materials to absorb oil (water) from oil/water combinations. Many types of oil absorption materials, such as activated carbon, wool fiber, rice straw, zeolite, lamellar graphite, and commercial sponge, have been extensively researched up to this point (Xie et al. 2019; Alghunaimi et al. 2019). Due to its superior mechanical qualities, large porosity, and high adsorption capacity, the sponge has garnered considerable attention (Li et al. 2016).

The following studies have provided extensive evaluations of the treatment of PWW. Yu et al. (2017) evaluated flotation, coagulation, biological treatment, membrane separation technology, combined technology, and an advanced oxidation process to see which was the best treatment to get rid of the pollution. Jamaly et al. (2015) performed a complete review of all the current and recently developed ways to OWWT. This is a look at new and innovative ways to deal with oily waste treatment. More precisely, Ezugbe and Rathilal (2020) did a very complete inspection of the most prominent membrane technologies for wastewater treatment, as well as their advantages and disadvantages, and even some membrane-related challenges, like fouling and how modules are built. Recently, Zhang et al. (2020) came up with a new way to separate oil and water. Some of the materials that have been given attention to include metal mesh, natural textile or synthetic membrane material, aerogel, sponge, foam, and smart controllable special wettable separation materials.

However, there hasn't been any recent work on bibliometrics for the PWWT or OWWT. It is important to learn about the history of research in order to better understand how research has changed and what the future holds. Thus, a thorough bibliometric overview of the research topics will assist both present and future scientists in determining where gaps exist and how to close them in order to expand their studies.

The purpose of this study is to combine bibliometric and information visualization analysis in order to ascertain the features and trends of research on oily wastewater treatment, with a particular focus on petrochemical wastewater. Based on the publications from 2000 to 2021, A complete and multi-perspective overview of the study on oily wastewater was presented using multiple analytical approaches from diverse perspectives. This study was conducted in four primary areas using a variety of analytical objects: characterization of research publication, countries' performances and collaborations analysis, keyword analysis (including frequency distribution of the keyword analysis, the transformation of the keyword combination across time, and exploring changes in rank over time), and journal analysis. Additional research is required for any other type of oily wastewater.

Materials And Methods

Bibliometric analysis

Bibliometrics analyzes the structure, features, and patterns of fundamental science and technology, using statistical approaches to explore the dispersed structure, quantitative connection, dynamic pattern, and quantitative management of document information (Du et al. 2014). It is a sophisticated strategy used by contemporary scholars all over the world to analyze developing trends in certain knowledge sets (Jain et al. 2022).

The bibliometric analysis also aids in the provision of a thorough overview and categorization of previous and current research, as well as the determination of future avenues for research in this subject. It enables the simultaneous examination of hundreds of documents using mathematical statistics methods and effectively grasps research hotspots.

Methodology and data sources

This study's approach consists of five stages: data extraction and identification, data screening, eligibility analysis, and ultimately bibliometric analysis. The Web of Science (WoS) database was used to conduct the literature search on 2022-02-25. The “Web of Science Core Collection” includes most of the major publications and is used in a broad range of scientific areas (Zhang et al. 2017b). Data from the core collection of the Science Citation Index Expanded (SCI-E) was used in the bibliometric study. Clarivate Analytics' ISI Web of Science was used as the source of the data. The literature search was limited to articles written in English from 2000 to 2021. Topics (title, abstract, author keywords, keywords plus®) were explored to find suitable information. In this study, only petrochemical effluent was examined, and no other oily wastewater types were included. Fig. 1 illustrates the search query.

Analysis tools

The bibliometric analysis of the WoS database was conducted using different software. The statistical data, such as annual trending countries' publications and journals' impact factors, were calculated by "Microsoft Excel". The core collaboration networks between keywords and countries were shown using VOSviewer (version 1.6.17). Also, the program is free to use by people who study bibliometrics (van Eck and Waltman 2010). In addition to the network analysis, the VOSviewer was also utilized to detect keyword clusters (Ding and Yang 2020).

Finally, Cortext Manager was used to examine the corpus of the articles' metadata files and determine their content. CorText Manager is an online tool for bibliometric analysis. It may be used to do statistical network analysis in a variety of areas of study. The CorText Manager's bibliometric data illustrates where research is currently and where it is leading. They also show what current fields are coming up (INRA 2020).

The Results And Discussion

Characterization of research publications

The total of 2457 publications is divided into 4 categories and is shown in Fig. 2. Articles, as the most frequent type, made up 91% (2238 records) of the total records. Review and proceedings papers were prepared for 4.3% (106 records) and 3.2% (79 records) of the records, respectively. Other types of records (meeting abstracts, early access, corrections, editorial materials, and letters) were the most uncommon, making up less than 1.5% of all the records. This report exclusively studies the major publishing type, articles.

The articles published in English accounted for 98.65% (2208 articles) of the total articles. 0.40% (9 articles) of the articles were in Chinese. It was less than 0.94% (30 articles) of the other languages, including Spanish, Polish, Portuguese, Russian, Japanese, and Serbo Croatian. In this research, only English-language articles were considered.

Country performance and collaboration patterns

The authors' addresses were obtained and used to assess the contributions of various countries. As a result, it was found that the authors originated from 86 countries. Of these, the authors have collaborated in 79 different places. By looking at Table 1, it will be clear which 20 countries are the most productive when it comes to the number of total papers that have been published. It also shows how many papers each country has been cited for, the total number of citations for each country, and the h-index for each country. Furthermore, the number of articles written by the top five countries each year is shown in Fig. 3.

Table 1 From 2000 through 2021, the top 20 producing countries contributed to publications.

Countries/Region	TP (R)		Percentage (%)	h-index (R)		AC/TP (R)		TC (R)		TS (R)	
Peoples R China	964	(1)	43.6	66	(1)	20.54	(11)	19802	(1)	202	(1)
Iran	288	(2)	13.0	36	(3)	18.97	(15)	5463	(2)	71	(3)
USA	150	(3)	6.8	38	(2)	35.17	(2)	5269	(3)	89	(2)
India	135	(4)	6.1	25	(6)	18.9	(16)	2551	(4)	37	(9)
Brazil	101	(5)	4.5	26	(4)	22.22	(10)	2244	(5)	23	(14)
Canada	80	(6)	3.6	26	(5)	27.13	(5)	2167	(6)	58	(5)
Malaysia	77	(7)	3.4	21	(8)	18.31	(18)	1410	(8)	48	(6)
Australia	49	(8)	2.2	21	(9)	25.82	(7)	1247	(9)	27	(12)
Egypt	46	(9)	2.0	17	(11)	22.57	(8)	1038	(11)	21	(15)
Turkey	45	(10)	2.0	16	(13)	22.36	(9)	1006	(12)	31	(10)
South Korea	42	(11)	1.9	15	(15)	19.17	(13)	805	(14)	17	(17)
Singapore	40	(12)	1.8	22	(7)	45.58	(1)	1823	(7)	70	(4)
Spain	38	(13)	1.7	16	(14)	19.08	(14)	725	(16)	38	(8)
Taiwan	38	(14)	1.7	15	(16)	18.37	(17)	698	(17)	13	(18)
Saudi Arabia	35	(15)	1.5	13	(17)	32.11	(3)	1124	(10)	5	(20)
England	34	(16)	1.5	17	(12)	26.53	(6)	795	(15)	45	(7)
Italy	33	(17)	1.4	13	(18)	15.21	(19)	502	(19)	24	(13)
Germany	32	(18)	1.4	18	(10)	30.31	(4)	970	(13)	20	(16)
Japan	31	(19)	1.4	12	(19)	19.61	(12)	608	(18)	31	(11)
Poland	26	(20)	1.1	9	(20)	11.65	(20)	303	(20)	9	(19)

Note: TP: the total number of papers; Percentage (%): the total number of each country’s papers per 2208; AC/TP: Average Citation per paper; TC: Total Citation; TS: Total link strength; R: It denotes a country's rank in various indicators (TP, AC/TP, TC, TS). The United Kingdom contained publications from Northern Ireland, Scotland, Wales, and England.

Peoples R China’s article output ranked first, accounting for 43.6% of the total records, but the average citations per paper ranked 11th, and the h index ranked first. It’s worth noting China has the most article citations among others, around 19802 times; it has the strongest total link strength, which shows China has cooperated in 202 article productions. China started in 2000 with the publication of an article by Cai et al. (2000) who used MnO_2 membranes for treating oil refinery wastewater with adequate results. After 2007, the growth trend of article publishing was positive, except for 2010 and 2013, which were accompanied by a slight decline, as shown in Fig. 3.

Iran published 11.8% of the total publications and performed poorly in the average citations per paper (18.65, ranked 18st) and the h-index (36, ranked 3rd). Fig. 3 shows that Iran has been so erratic in producing articles that no article was published on petroleum wastewater in 2002, 2004, and 2006. It had the best performance in 2019 and has been declining since then.

The USA published 6.8% of the total publications, performed well in the h-index (38, ranked 2nd) and collaborated with other countries in 89 article submissions. Since 2000, the United States has followed an intermittent pattern in publishing papers, as seen in Fig. 3. In a sense, there was no article written in 2008. It's worth mentioning that from 2014 to 2020, the number of articles published increased. The majority of papers were submitted in 2020, although this tendency shifted in 2021.

It was noticed that Singapore's publications with the highest average citation per publication (45.58) ranked 1st. After that, the USA showed the best performance, with higher academic influence ranking 2nd. Other countries such as Saudi Arabia, Germany, and Canada ranked 3rd to 5th in the average citations per paper, respectively.

VosViewer Software was used to analyze the global academic collaboration between the top 20 most productive countries; the results are shown in Fig. 4. The size of each point, which represents a country, was based on the number of publications in that country. Cooperative relationships were shown by the lines that connected these points. The thickness of the lines was based on the number of collaborative publications, which was a good indicator of how close the relationship was. It was up to the affiliations of the co-authors and how much they worked together on the research project to determine which countries worked together (Bozeman et al. 2013).

From Fig. 4, it can be seen that China has the largest number of collaborative publications, while the large size of the node, shows a high frequency of the items. In addition, China has the strongest cooperatives with the USA and Australia, and a thick link line indicates that the two countries have a tight relationship.

The network can be broadly divided into five clusters, which are the clusters and links. Cluster1 contains: Brazil (14), England (16), India (21), Spain (13), Italy (11), Taiwan (11), and cluster2: japan (11), Saudi Arabia (21), Egypt (11), south Korea (11), and cluster3: Canada (22), Iran (26), Malaysia (21), Turkey (4), and cluster4: Peoples R China (38), USA (29), Australia (17), and cluster5: Singapore (9), Germany (15).

The distribution of leading countries in the field of PWWT is shown in Fig. 5. They can be divided into two groups. One of them is the largest oil consuming countries that pay special attention to PWWT, such as China, the United States, India, Brazil, and European countries. For example, beginning in January 2015, China implemented a Water Pollution Control Action Plan with an emphasis on the preservation and conservation of water resources(Chen et al. 2020). Another group is countries which are the biggest oil producers, like Iran, Saudi Arabia, and Egypt. As seen in Fig. 5 ten Asian countries, two North American countries, five European countries, one Oceania country (Australia), one South American country (Brazil), and one African country (Egypt) are among the top twenty countries. Asia, America, and Europe, respectively, have the highest concentration of published papers on this topic.

The distribution of journals

A total of 2208 articles related to literature on PWWT research all over the globe from 2000 to 2021. The journal distribution of the top 20 publications, which published more than 42% of the total articles, is shown in Table

2. In this study, IF (Impact Factor) was used to compare journals' quality. Overall, IF is regarded as a reliable predictor of a journal's quality (Mao et al. 2015).

Table 2 Top 20 most productive journals from 2000 to 2021.

Journals	TP (R)		IF (R)		TC (R)	
Desalination and water treatment	123	(1)	1.254	(18)	912	(9)
Separation and purification technology	85	(2)	7.312	(8)	1962	(6)
Journal of membrane science	63	(3)	8.742	(7)	3108	(2)
Water science and technology	61	(4)	1.915	(17)	464	(14)
Journal of hazardous materials	59	(5)	10.588	(2)	3148	(1)
Bioresource technology	51	(6)	9.642	(3)	2176	(5)
Desalination	50	(7)	9.501	(4)	2675	(3)
Chemical engineering journal	45	(8)	13.273	(1)	2278	(4)
Journal of water process engineering	42	(9)	5.485	(11)	464	(15)
Rsc advances	41	(10)	3.361	(14)	951	(8)
Environmental science and pollution research	40	(11)	4.223	(13)	390	(17)
Journal of environmental chemical engineering	38	(12)	5.909	(10)	345	(18)
Environmental technology	35	(13)	3.247	(15)	466	(13)
Colloids and surfaces a physicochemical and engineering aspects	33	(14)	4.539	(12)	611	(11)
Fresenius environmental bulletin	32	(15)	0.489	(20)	102	(20)
Chemosphere	31	(16)	7.086	(9)	876	(10)
Journal of cleaner production	31	(17)	9.297	(5)	504	(12)
Separation science and technology	29	(18)	2.475	(16)	406	(16)
Acs applied materials interfaces	28	(19)	9.229	(6)	1218	(7)
Oxidation communications	28	(20)	0.541	(19)	118	(19)

Note: TP: the total number of papers; IF: Journal’s Impact Factor in 2021; TC: Total Citation; R: It denotes a country's rank in various indicators (TP, IF, TC).

According to the results of Table 2, the majority of the journals mentioned in the table had a high IF value, with 60% of them having values that ranged from 4.5 to 13.2. As a result, it indicated that this issue was prevalent among the most prestigious publications. “Desalination and Water Treatment” is the most productive journal with 123 articles; although its IF is 1.254 (IF rank: 18). It is followed by the “Separation and Purification Technology” with 85 articles (IF rank: 8) and the “Journal of Membrane Science” with 63 articles (IF rank: 7). It's worth mentioning that the “Chemical Engineering Journal” with the highest IF (13.273) published 45 articles.

With regard to the citations, the “Journal of Hazardous Materials” with 3148 citations, has the best performance among the journals. It can be considered a key journal having a significant effect on PWWT research. After that, “Journal of Membrane Science” with 3108 citations, has the second rank.

The most 180 day usage articles

The most 180 days usage articles are collected from the web of science core collection and sorted in descending order based on the usage count for the past 180 days in Table 3. The separation and purification technology journal performed well with 4 articles (Qiu et al. 2021; Su et al. 2021; Xue et al. 2021; Zhang et al. 2021b). Each of the Journals of Membrane Science and ACS Applied Materials & Interfaces published 2 articles (Ma et al. 2020, 2021; Fan et al. 2021; Hou et al. 2021).

Table 3 Most 180 day usage articles

No.	Keyword	TC	180 Day Usage Count	journal	Year	Ref.
1	durable; zeolitic imidazolate framework-8@thiolated graphene; nanofibrous membrane; self-cleaning; oil/water separation; photodegradation of organic contaminants; antibacterial	88	134	ACS Applied Materials & Interfaces	2020	(Ma et al. 2020)
2	emulsion separation; janus membrane; silicon dioxide; hexadecyltrimethoxysilane	5	133	Separation And Purification Technology	2021	(Qiu et al. 2021)
3	graphene-based microspheres; metal-organic frameworks; oil-water separation; superhydrophobicity; superoleophilicity	119	124	Angewandte Chemie-International Edition	2019	(Gu et al. 2019)
4	antifouling; microfiltration membrane; nanohydrogel; oil/water separation; zwitterionic compound	208	124	Advanced Functional Materials	2018	(Zhu et al. 2018)
5	superhydrophobic; self-healing; robust; electrospun nanofibrous membrane; wastewater purification	16	110	Journal of Membrane Science	2021	(Ma et al. 2021)
6	photothermal; superwetting; solar evaporation; photocatalysis; clean water	16	108	Chemical Engineering Journal	2021	(Zhu et al. 2021)
7	metal-organic frameworks; superhydrophobic coatings; fast self-healing; reversible dynamic bond; emulsion separation	0	96	Separation And Purification Technology	2021	(Zhang et al. 2021b)
8	oil-spill cleanup; waste-water treatment; exfoliated graphite; coated mesh; heavy oil; superhydrophobic surfaces; nanocellulose aerogels; hydrophobic properties; magnetic composites; polyurethane foams	821	92	Journal of Materials Chemistry A	2014	(Xue et al. 2014)
9	oil-water separation; agarose hydrogel; ecofriendly; high separation efficiency	10	86	Colloids And Surfaces A-Physicochemical And Engineering Aspects	2018	(Sun et al. 2018)
10	tetradecylamine; mxene; melamine sponge; oil/water separation	15	72	Separation And Purification Technology	2021	(Xue et al. 2021)
11	phase inversion; polyimide; porous membrane; oil/water separation; heavy oil	1	67	Journal of Membrane Science	2021	(Hou et al. 2021)
12	nanoalumina; nanocellulose; nanocomposite aerogel; solvent-free; oil and organic solvent adsorption	16	63	Journal of Colloid And Interface Science	2021	(Zhou et al. 2021)
13	corrosion resistant; oil/water separation; polyphenylene sulfide; reduced graphene oxide; joule heating	15	61	ACS Applied Materials & Interfaces	2021	(Fan et al. 2021)

14	oil/water separation; solution blow spinning; tio2 nanorods; superhydrophobic; photocatalytic	4	58	Separation And Purification Technology	2021	(Su et al. 2021)
15	dead-end microfiltration; surface-properties; flux decline; cross-flow; mesh film; emulsions; demulsification; permeation; mixtures; coatings	856	57	Nature Communications	2012	(Kota et al. 2012)

Note: TC: Times Cited (All Databases);

Ma et al. (2020) used a combination of facile electrospinning and in situ hydrothermal synthesis methods to successfully fabricate a superhydrophobic nanofibrous membrane. It was rated the best by 134 readers. In the second rank, Qiu et al. performed a Janus membrane with asymmetric wettability which separates oil in water with 99.975% efficiency (Qiu et al. 2021). Some researchers have been inspired by this work (Liu et al. 2022b; Zuo et al. 2022). In third place, Zhan et al. published a work on novel super-hydrophobic/super-oleophilic materials (Gu et al. 2019).

Top articles with the strongest citation burst

The most active field of research during a certain time period can be seen through citation burst, when the number of citations to a certain reference goes up dramatically during that time (Liu 2013). The primary citation burst measures are burst strength and burst duration. From 2208 papers, our investigation identified 643 citation bursts. Some articles which play a lead role in this topic, with recent burst duration are shown in Table 4.

Recently, burst articles focus on the development of membrane technology for oil removal; for instance, Wei et al. provide an up-to-date evaluation of the most recent research on selective membrane materials for extremely effective oil–water separation using the notion of exceptional wettability. This article was published in 2018 and its burst period was detected between 2020 and 2021. Membranologists are paying more attention to wetting on membrane surfaces. Furthermore, in terms of membrane classifications, definitions, general design concepts, features, and applications, a systematic knowledge of the new advanced membrane materials with specialized wettability is offered by Wei et al. (Wei et al. 2018). It leads to current work on oil-water separation utilizing wettable membranes (Sui et al. 2021; Cheng et al. 2022; Kim et al. 2022; Zhu et al. 2022; Duan et al. 2022).

Also, Tang et al. have fabricated a novel superhydrophobic and superoleophilic nanofibrous membrane by an in situ polymerization method (Tang et al. 2013). There are some works which have been inspired by this publication since 2020 (Qu et al. 2020; Wang et al. 2021). In addition, owing to a rise in the usage of superhydrophobic materials to remediate PWW, superhydrophobic PVDF membranes are receiving a lot of attention (Jiang et al. 2020; Zeng et al. 2021). Zhang et al. used a phase-inversion procedure to create superhydrophobic-superoleophilic PVDF membranes (Zhang et al. 2013).

Keywords analysis

A total of 7795 types of keywords were obtained, but only 766 of them were utilized five times or more. Fig. 6 shows the co-occurrence network visualization of the 766 keywords. Each curve indicates the co-occurrence connection between the two terms linked, and each circle shows a keyword. Due to the obvious label optimization for a better analysis of Fig. 6, certain keywords are masked in the figure.

The keywords appearing in Fig. 6 can be separated into 6 clusters, each with a distinct color scheme:

Cluster 1 (in red): This cluster mostly contains keywords relating to the biological treatment method, such as "degradation", "biodegradation", "activated-sludge", "bioremediation", "membrane bioreactor (MBR)", "sequencing batch reactor (SBR)".

Cluster 2 (in green): This cluster primarily contains keywords connected to the separation process, such as "oil/water separation", "membranes", "fabrication", "oil", "water", "surface", "wettability", "nanoparticles", "graphene oxide", "superhydrophobic", "coated mesh", "electrospinning", "sponge".

Cluster 3 (in blue): This cluster mostly contains keywords associated with the oxidation process, such as "oxidation", "hydrogen peroxide", "kinetics", "TiO_2", "ozonation", "photocatalytic degradation", and "optimization".

Cluster 4 (in yellow): This cluster primarily contains keywords connected to the filtration process, such as "performances", "oily wastewater", "separation", "emulsions", "ultrafiltration", "microfiltration", "filtration", "surface modification", "PVDF (Poly vinylidene fluoride) membranes".

Cluster 5 (in purple): This cluster mostly contains keywords relating to the adsorption process, such as "adsorption", "chitosan", "activated carbon", "sorption", and "aqueous-solution".

Cluster 6 (in Turquoise): This cluster mostly contains keywords associated to the electro-chemical methods, such as "coagulation/flocculation", "electro-coagulation", "recovery", "surfactant", and "flocculation".

The major directions of the research on PWWT can be achieved by analyzing the six clusters mentioned above. In the first cluster, "Membrane bioreactor (MBR)" is a link between biological methods and membranes. This process has received a great deal of interest for the treatment of PWW, as reported by Pajoumshariati et al. (2017). In comparison to conventional wastewater treatment procedures (mainly the activated sludge process (ASP)), MBR can be successfully employed with a low footprint and high-quality effluent output (Maryam Tavakolmoghadam 2022). According to Huang et al. (2020) MBR treating petrochemical wastewater demonstrated excellent organic and ammonium removal efficiencies of more than 80% and 99.9%, respectively.

As shown in Fig. 6, the terms "MBR" and "membrane fouling" were found to be strongly related in a keyword analysis. When the membrane came into contact with industrial effluent, the pore size of the membrane shrank or became blocked, lowering the separating capacity. As a result, membrane module optimization and pollution prevention have become key study areas in treating wastewater. Many researchers worked on developing dynamic response models, developing novel membrane modules, and developing process improvement strategies (Chai et al. 2016; Praveen and Loh 2019).

The keyword analysis at cluster 1 also showed that "Sequencing batch reactor (SBR)" is one of the major research topics. Similarly, Tantak et al. (2014) found that the SBR process is one of the most widely used aerobic treatment processes for municipal and industrial wastewater, including wastewater from refineries and petrochemical plants. It has been widely employed as an alternative to ASP for the treatment of PWW on an industrial scale (Thakur et al. 2014).

As seen in Fig. 7, "oil/water separation" is a critical topic that has received increased attention in recent years. Gupta et al. (2017) similarly reported that oil/water separation has significant practical consequences for dealing with industrial oily wastewater and other oil/water pollutants.

The membrane is very much in contact with the rest of the oil/water separation methods like nanoparticles in the second cluster. Many studies have attempted to improve nanocomposites membranes by incorporating various nanoparticles such as carbon nanotubes, graphene oxide (GO), and zeolites (Masoumi Khosroshahi et al. 2018; Modi and Bellare 2019; Kazemi et al. 2021). GO has been shown to be a strong hydrophilic coating material with a lot of potential for improving the flux or antifouling performance of various membranes, including mesh, phase-inversion membranes, and inorganic membranes (Dong et al. 2014; Huang et al. 2015; Hu et al. 2015).

Furthermore, as shown in Fig. 7, current research has mostly concentrated on surface superwettabilities such as superhydrophobicity, superhydrophilicity, superoleophobicity, and superoleophilicity as similarly reported by many researchers (Zhang et al. 2021a; Liu et al. 2022a). For instance, the one-step synthesis of environmentally friendly superhydrophilic and superhydrophobic sponges was developed by Lee et al. (2019) for oil/water separation. In addition, it found that membranes with superhydrophilic and underwater-superoleophobic surfaces can be successfully applied to cleaning oily wastewater by altering the free energy and surface micro-nanostructure of the material (Cheng et al. 2020; Zhang et al. 2020b).

As shown in the second cluster, “Electrospinning” is clearly linked to “oil/water separation” and “fabrication”. This method has been extensively utilized to create polymer-based microfiltration membranes with densely interconnected pore structures, enormous porosity (>90 %), configurable functionality, and improved structural stability (Choong et al. 2014; Ahmed et al. 2015). Lin et al. (2012) launched this discussion in 2012; They investigated the oil sorption capabilities of these porous polystyrene (PS) fibers as sorbents to see whether they might be used to clean up oil spills, and they made PS fibers by electrospinning a polymer solution directly. Newly, Du et al. (2021a) have suggested a simple electrospinning approach for fabricating an antifouling and hydrophilic PVDF-TiO2 nanofiber membrane for oil/water emulsion separation, and they demonstrate excellent performance in oil/water emulsion separation with an efficiency of up to 98.4%.

In the third cluster, the keywords “ozonation” and “hydrogen peroxide” are fully related to the oil removal by the oxidation process. Britto et al. (2021) compared two inexpensive oxidants (hydrogen peroxide and oxygen) in order to solve a potential industrial challenge with phenol removal from a petrochemical plant.

In the fourth cluster, various filtration topics and challenges like “microfiltration (MF)”, “ultrafiltration (UF)”, “ceramic membrane”, and “membrane fouling” are presented. Application of membrane for PWWT has been actively explored in the previous decade owing to its capacity to remove the majority of chemicals, inorganic and organic components from wastewater (Abuhasel et al. 2021). MF and UF are two membrane separation methods that have been shown to be effective in separating oil-water emulsions (Zhang et al. 2014; Padaki et al. 2015). The driving mechanism for MF membranes is a low static differential pressure, which is based on size exclusion or particle capture. As a result, MF membranes are low-cost, high-flux, and high-selectivity technologies (Zhang et al. 2017a). UF membranes are more effective than MF membranes in terms of membrane pore size. Oil may also be separated from water using nanofiltration and reverse osmosis, which is particularly useful for high-salinity water (Jamaly et al. 2015).

The fifth cluster focuses on the adsorption process for PWWT. The terms “activated carbon (AC)”, “kinetics”, and “chitosan” have a strong link to adsorption. Adsorption is one of the most efficient methods for advanced wastewater treatment, and AC is the most frequently used adsorbent with good adsorption capacity (Zhang et al. 2005). Recently, there has been some research on combining activated carbon with other technologies. Manawi et al. (2022) designed and tested a new adsorptive ceramic membrane doped with AC for the removal of oil and phosphate from water in order to improve membrane performance.

In the last cluster, "electrocoagulation (EC)" has a good relationship with "removal", "coagulation/flocculation", and "oxidation". The EC process, in comparison to the chemical coagulation process, gives better elimination capabilities for comparable particles with no chemical additives. The EC method has many advantages, including ease of operation, simple equipment, shorter remediation times, reduced sludge formation, and lower sludge purification costs (Sharma and Simsek 2019).

The contingency table

The lexical term extraction approach, which is used to extract keywords from metadata files in WoS search results, is supported by the CorText Manager (Ruiz Fabo and Poibeau 2019). The term extraction algorithm can discover 80 significant terms in the selection while taking into account the frequency of occurrence in a phrase. As a result, the script picks words based on a trade-off between frequency and specificity where the phrases are detected with at least five co-occurrences. As illustrated in Fig. 8, this method was used to construct contingency matrices for the WoS results of this investigation, with the number of nodes limited to 12 for the given journal name and keyword fields. The degree of inter-relationship between the journal name and keyword is shown using a heat map. The heatmap's numerical scale, which ranges from -4 to 4, depicts a comparison of the joint count of the selected two fields (journal's name and keyword) versus the projected co-occurrences (MATSUO and ISHIZUKA 2004).

The results show that "Bioresource Technology" and the term "petrochemical wastewater" are the most recognized. The journals "Membrane Science" and "Separation and Purification Technology" focus heavily on "oil/water separation", which is consistent with the aim and scope of these journals. Despite the proposed correlations, the "Desalination and Water Treatment", "Water Science and Technology", and "Desalination" journals have shown the lowest correlation with the terms "oil/water separation". In addition, "membrane" and "superhydrophobic" are the hot issues that are extensively studied by "Membrane Science" and "Separation and Purification Technology" journals, respectively.

The inter-temporal network stream

An inter-temporal network stream, known as a Sankey diagram, is created using CorText Manager's network mapping capabilities to evaluate the transformation of the keyword combination across time. One three-slice selection with a maximum node setting of 100 is used to do the network analysis. The dynamic portrayal of tubes in the Sankey diagram depicts the development of semantic clusters over time. A murky tube color indicates a greater relationship between the two detected terms, and vice versa. The tube thickness, on the other hand, reflects the co-occurrences of the two terms. The development of keywords is shown by the dynamic tube color and thickness through time in a Sankey diagram, which represents the historical alteration of the study area (Ubando et al. 2021).

For the results shown in Fig. 9, a diverging stream is depicted from the previous portion of 2008 with a keyword combination of "petrochemical wastewater & phenol". This was split into two, which are "petrochemical wastewater & biodegradation" and "oily wastewater & toc removal". This shows that in a span of 9 years (from 2007 to 2016), the keywords "petrochemical wastewater & phenol" have transformed into 2 distinct research areas.

The divergence of this stream as well as the transformation of the keyword show the dynamic evolution of the research field over time. After 2016 “petrochemical wastewater & biodegradation” transformed into “biodegradation & wastewater treatment” in 5 years (from 2016 to 2021).

In addition, the “fouling & microfiltration” was split into two streams. The first stream merged with “petrochemical wastewater & phenol” and transformed into “oily wastewater & toc removal” from 2007 to 2016. The second stream remained unchanged as “fouling & microfiltration”. After 2016, “fouling & microfiltration” merged with “membrane fouling & surfactant” to form “oily wastewater & ultrafiltration”.

An expanding stream is captured from 2016 to 2020 where the keyword “oil/water separation & oil absorption” expanded to the term “electrospinning & superhydrophobicity”. In this regard, different researchers fabricated some superhydrophobicity material by electrospinning method (Ma et al. 2018; Wu et al. 2019; Zhang et al. 2019; Feng et al. 2019; Wang et al. 2019; Semiromi et al. 2019; Jiang et al. 2021, 2022; Du et al. 2021b; Zhao et al. 2021).

Past, current, and future trend of keywords

The bump graph of the combined documents is shown in Fig. 10. The width of the tube in the bump graph represents the normalized occurrence of the terms in the abstract, title, and keywords (Ubando et al. 2021). As can be seen, the occurrence of the term “oil/water separation” increased considerably from 2007 to 2021, making it a trendy issue.

Some specific terms, such as “superhydrophobic”, “antifouling”, and “emulsion separation” grew in popularity and became hot issues between 2017 and 2021 in the fields of PWWT and oil/water separation. After 2015, the importance of certain subjects (such as “microfiltration”, “ultrafiltration”, “coagulation/flocculation”, and “phenol”) has decreased, although they are still being discussed by researchers. Between 2007 and 2021, the term “membranes” grew at a steady pace.

Fig. 11 shows the yearly evolution of the hot issues from Fig. 10. Clearly, “superhydrophobic” has the highest growth rate between 2018 and 2019. It also discovered an increase in academic research on “adsorption” since 2018.

Conclusions And Future Opportunities

Petrochemical wastewater (PWW) is a significant source of industrial pollution, including a variety of harmful organic contaminants. Treatment of PWW requires simple, efficient, and cost-effective technology. The present study examined the features and trends in PWW treatment research. A bibliometric analysis was performed to analyze 2457 publications that report research on petrochemical wastewater treatment (PWWT) from 2000 to 2021. The most common record type was articles, which accounted for 91 % of all entries. This analysis focuses only on the primary publishing types of English-language articles, which account for 98.75 % (2208 articles) of total articles. For further analysis, country performance, journals and keyword analysis were conducted. Results showed that the article production of the Peoples R China placed first, accounting for 43.6 % of all records, while the average citations per paper rated 11th, and the h-index scored first. The most publications were generated by People R China, Iran, and the United States of America (43.6 %, 11.8 % and 6.8 % of the total records, respectively). According to the breakdown of the top producing countries, they were divided into two groups. One of them was the largest oil consuming countries that pay special attention to PWWT, such as China, the United States, India, Brazil, and European countries, and the other group was countries that were the most oil producing countries, like Iran, Saudi Arabia, and Egypt.

According to the top articles with the strongest citation burst and the most 180 day usage articles, it was found that in recent years the majority of articles have focused on oil removal using membrane technology. They have a special concentration in PVDF membranes, superhydrophobic and superoleophilic nanofibrous membrane, and polymeric membranes.

VosViewer software was utilized to analyze international academic cooperation among the top 20 most productive countries. According to the results, China had the most collaborative publications and the strongest collaborations with the United States and Australia. Journal analysis revealed that the majority of journals had a high Impact Factor (IF) value, with 60% of them ranging between 4.5 and 13.2, indicating that this issue was widespread among high-quality publications. “Desalination and Water Treatment” was the most productive journal with 123 articles (IF rank: 18), followed by “Separation and Purification Technology” with 85 articles (IF rank: 8).

By utilizing contingency matrix analysis, it was found that “Bioresource Technology” journal focuses on the term “petrochemical wastewater”. “Membrane Science” is a publication that focuses on “oil/water separation” and “membrane”. In addition, “oil/water separation” and “superhydrophobic” are both popular topics in PWWT, according to the “Separation and Purification Technology” publications.

In addition, keyword evolution, keyword relationships, and keyword co-occurrence analysis were conducted. Six clusters are investigated based on keyword co-occurrence analysis, which is the study's focus in the field of PWWT. It was found that among PWWT technologies, biodegradation, ultrafiltration (or microfiltration), membrane separation, absorption (or adsorption), and oxidation were mostly studied according to the keyword frequency. Between 2017 and 2021, certain specialized terminology in the field of PWWT and oil/water separation rose in prominence and became hot concerns, such as “superhydrophobic”, “antifouling”, and “emulsion separation”. Clearly, the term “superhydrophobic” grew at the fastest pace between 2018 and 2019. Since 2018, there has been a rise in academic studies on “adsorption”. These findings are useful for academic researchers, practitioners, and policymakers, as well as those who are interested in further research in this field.

Abbreviations

OWW, oily wastewater; PWW, petrochemical wastewater; PWWT, petrochemical wastewater treatment; OWWT, oily wastewater treatment; BTEX, benzene, toluene, xylene, ethylbenzene; ET, electrochemical technology; WoS, Web of Science; SCI-E, Science Citation Index Expanded; Peoples R China, People's Republic of China; IF, Impact Factor; TP, the total number of papers; AC/TP, average citation per paper; TC, total citation; TS, total link strength; R, ranking; MBR, membrane bioreactor; ASP, activated sludge process; SBR, sequencing batch reactor; GO, graphene oxide; PVDF, poly vinylidene fluoride; UF, ultrafiltration; MF, microfiltration; PS, porous polystyrene; AC, activated carbon; EC, electrocoagulation;

Declarations

Author Contributions

All the authors contributed to the study’s conception. Mahdi Kalantari wrote the manuscript's initial draft. The final manuscript was read and approved by all writers. The original draft of the paper was written by Mahdi Kalantari, who also did the conception, literature search, data analysis, and discussion. Shabnam Sadri Moghaddam edited the manuscript and came up with the idea, analyzed the data, reviewed and edited it, led the discussion, and supervised the work. We appreciate Fereidon Vafaei's insightful commentary and review.

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Tables

Table 4 is available in the Supplementary Files section.

Figures

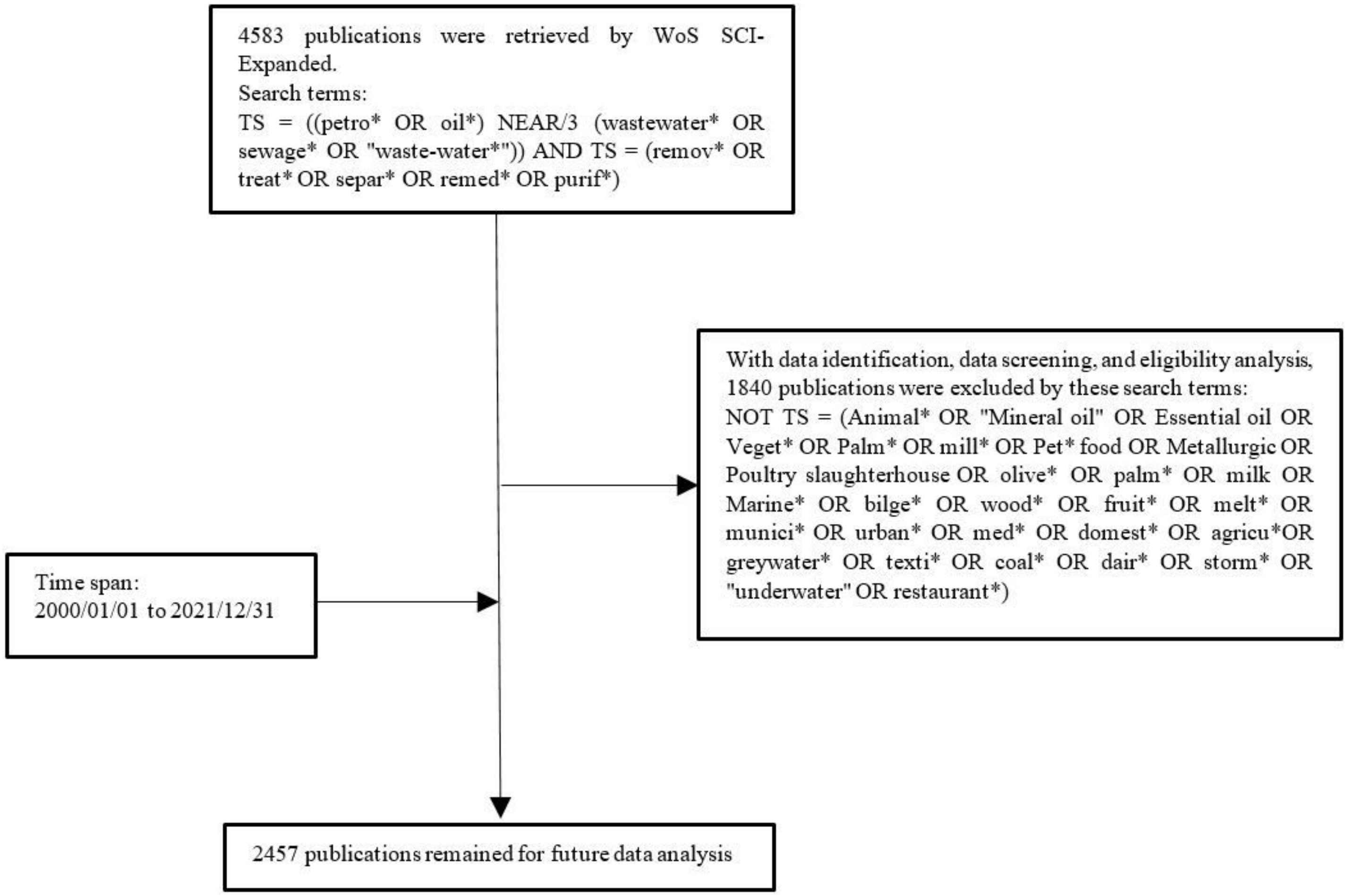

Figure 1

The search query for petrochemical wastewater treatment.

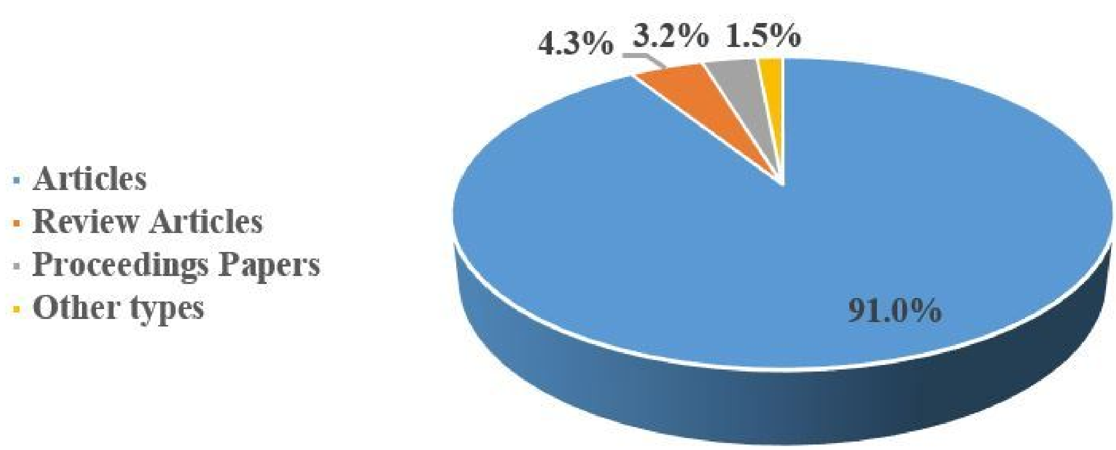

Figure 2

Publication categories from 2000 to 2021.

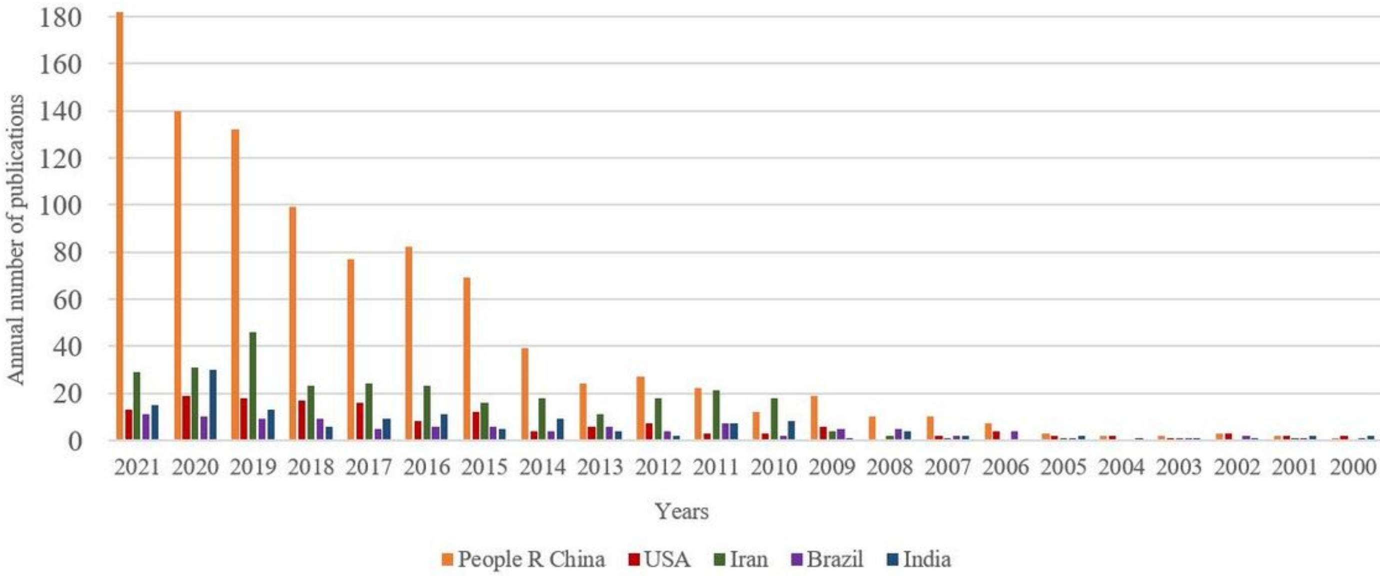

Figure 3

The top five countries' annual number of articles.

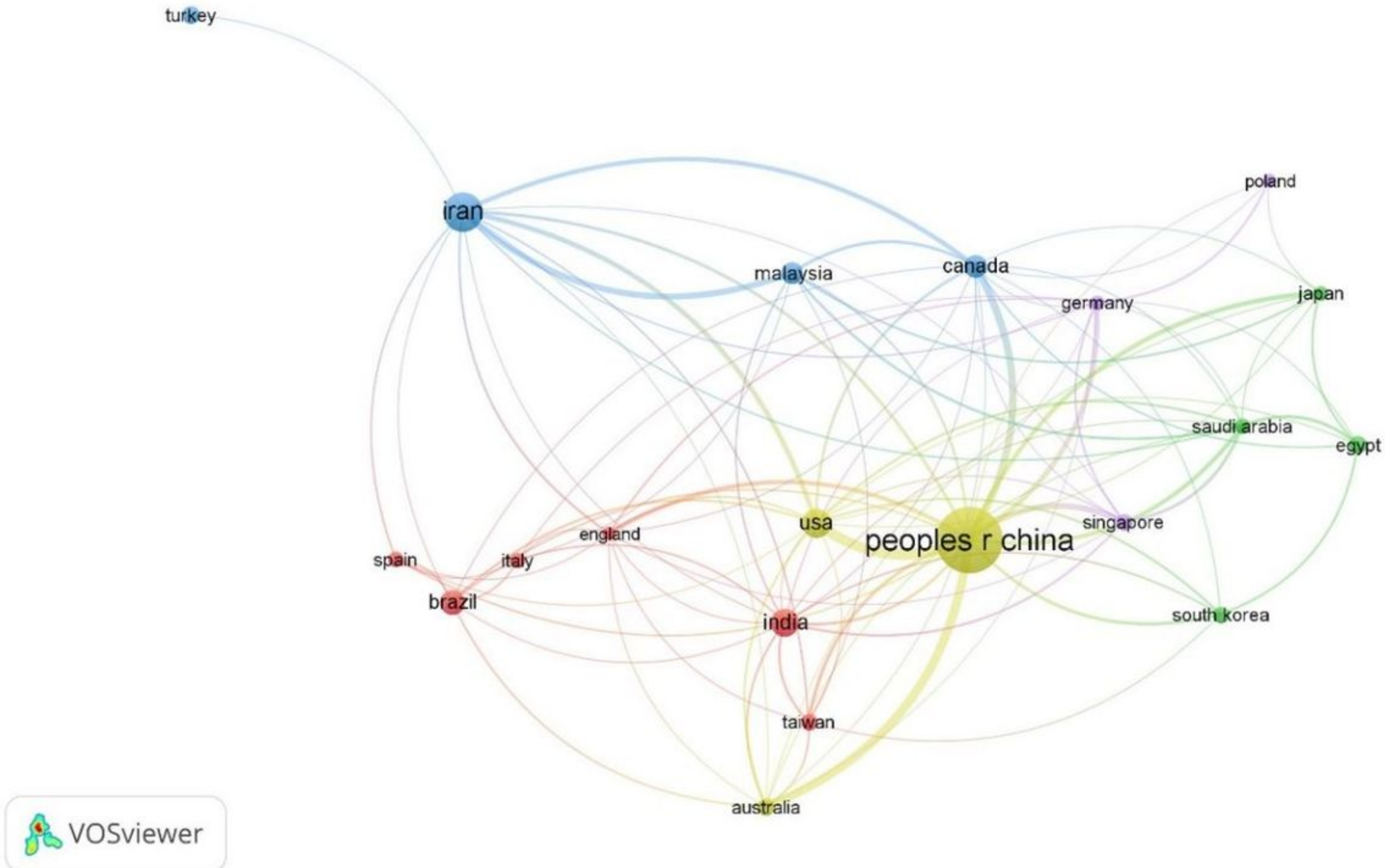

Figure 4

International collaboration amongst the world's top twenty productive countries.

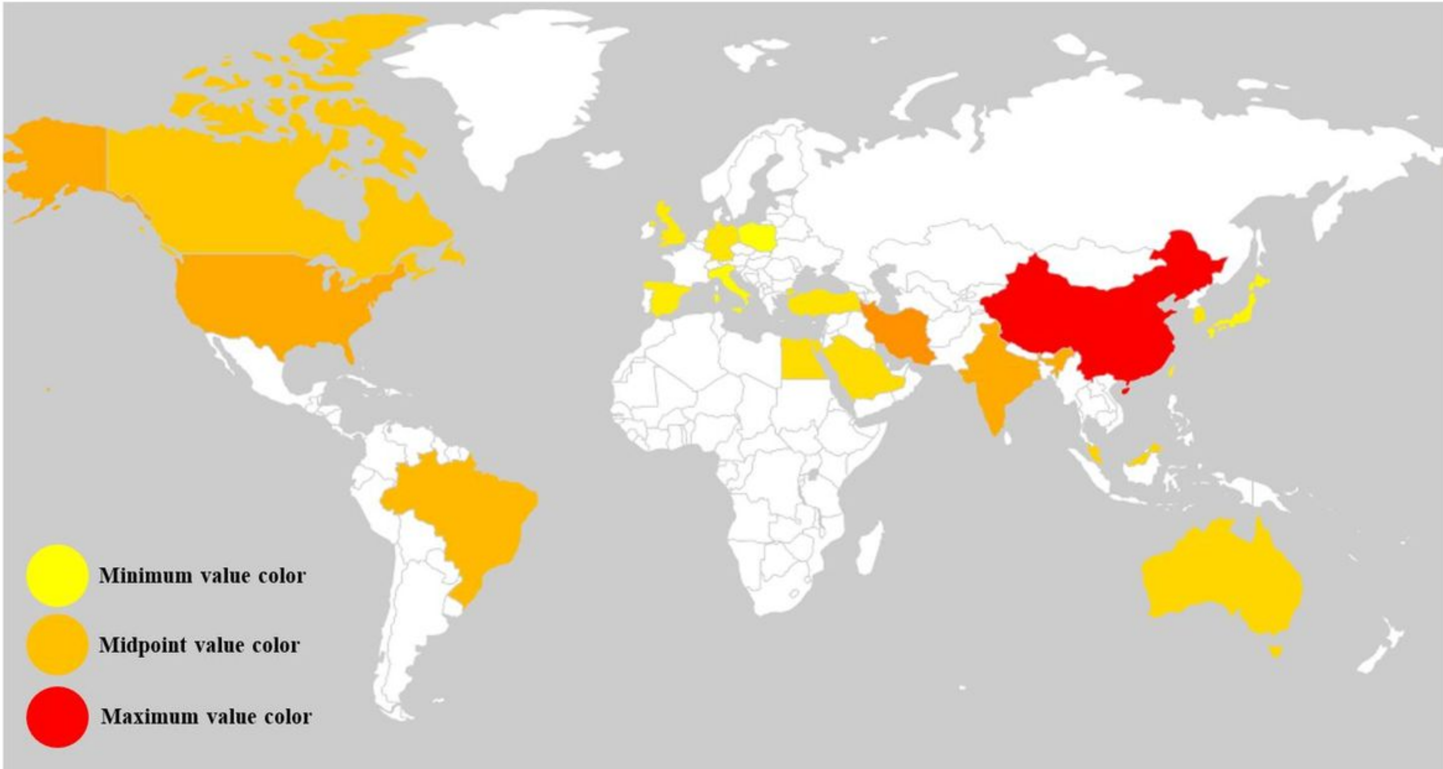

Figure 5

Geographical Heat Map of most productive countries.

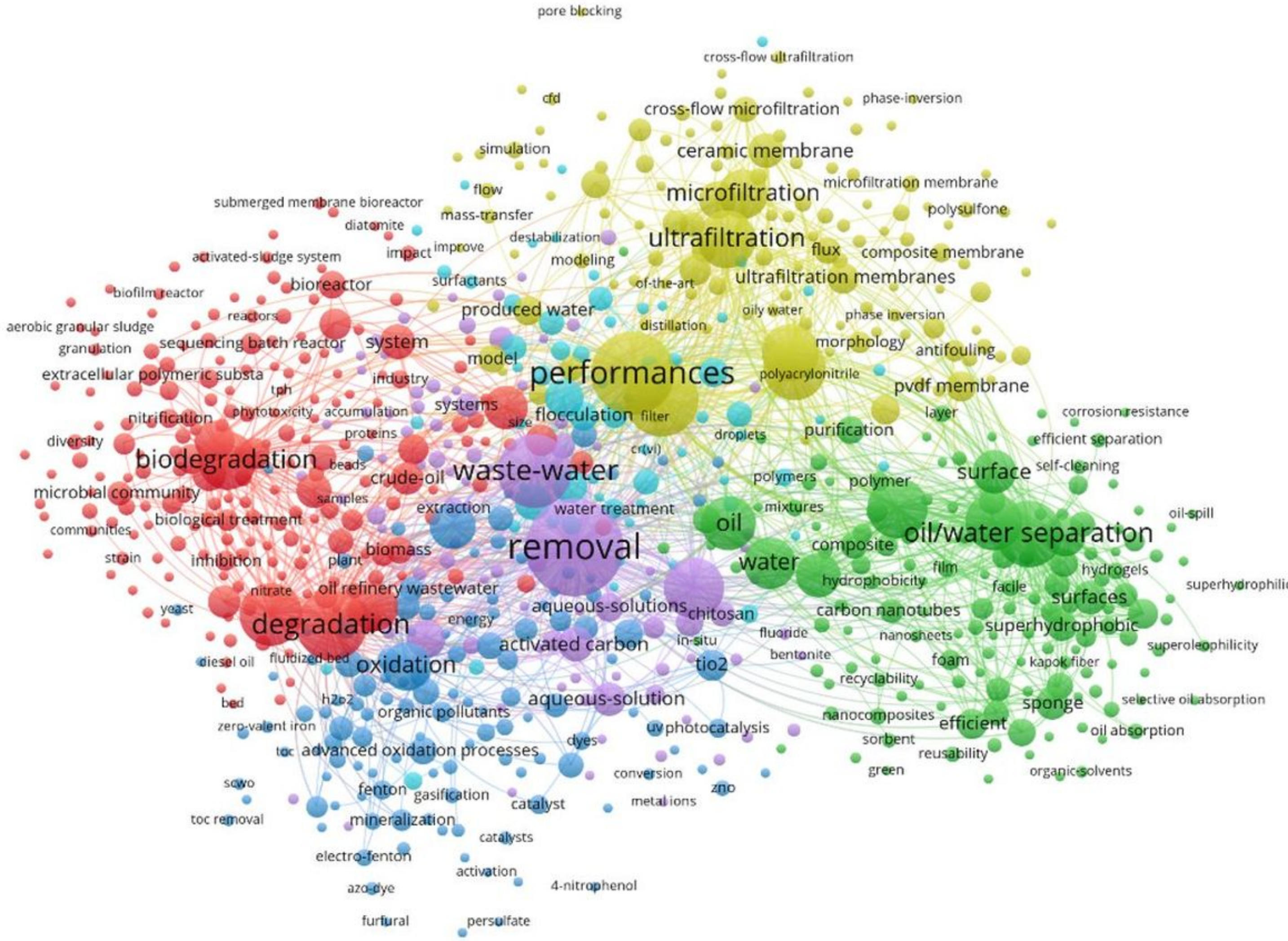

Figure 6

Cluster visualization and bibliometric co-occurrence of keywords.

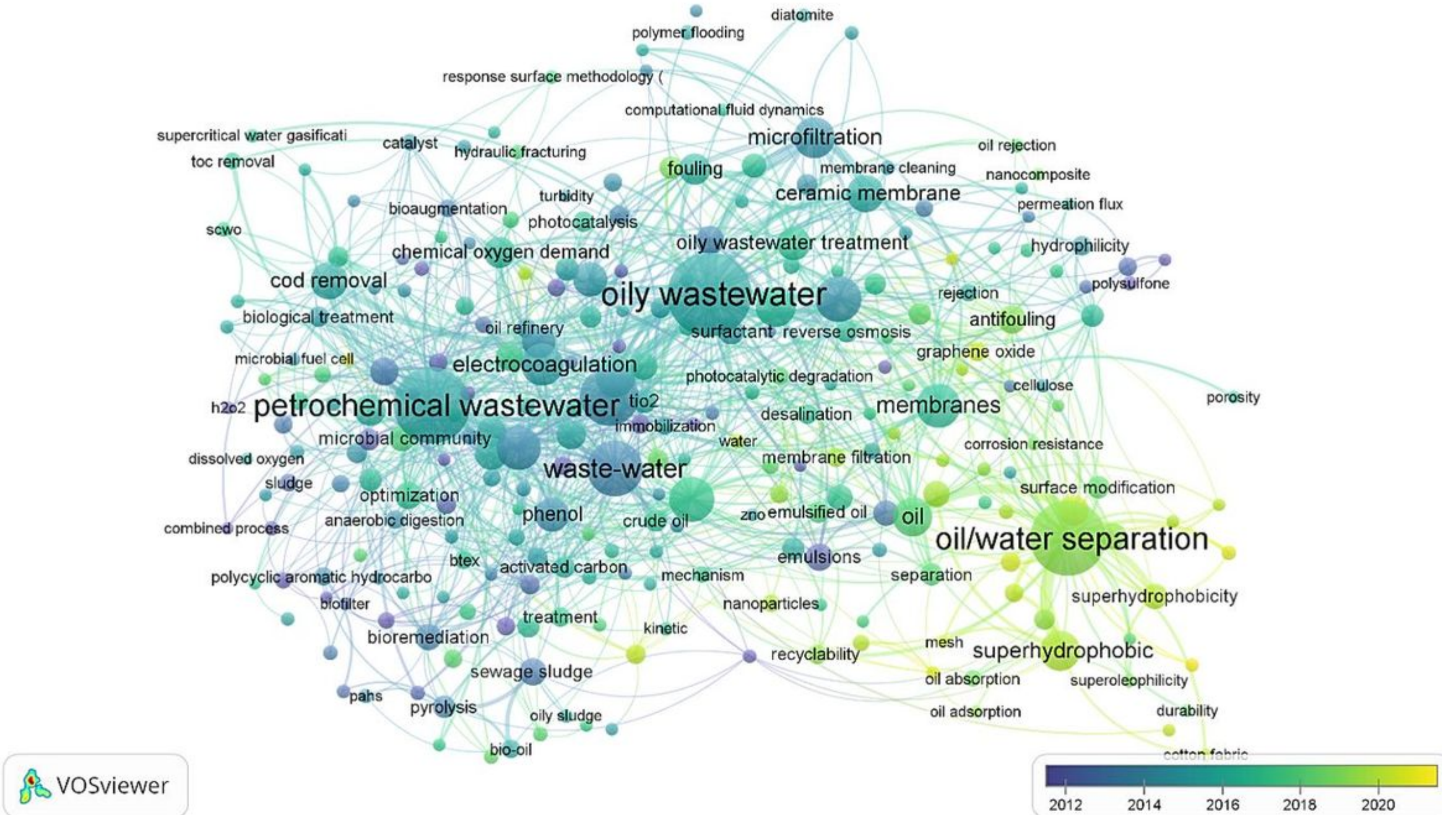

Figure 7

An overlay visualization on keywords.

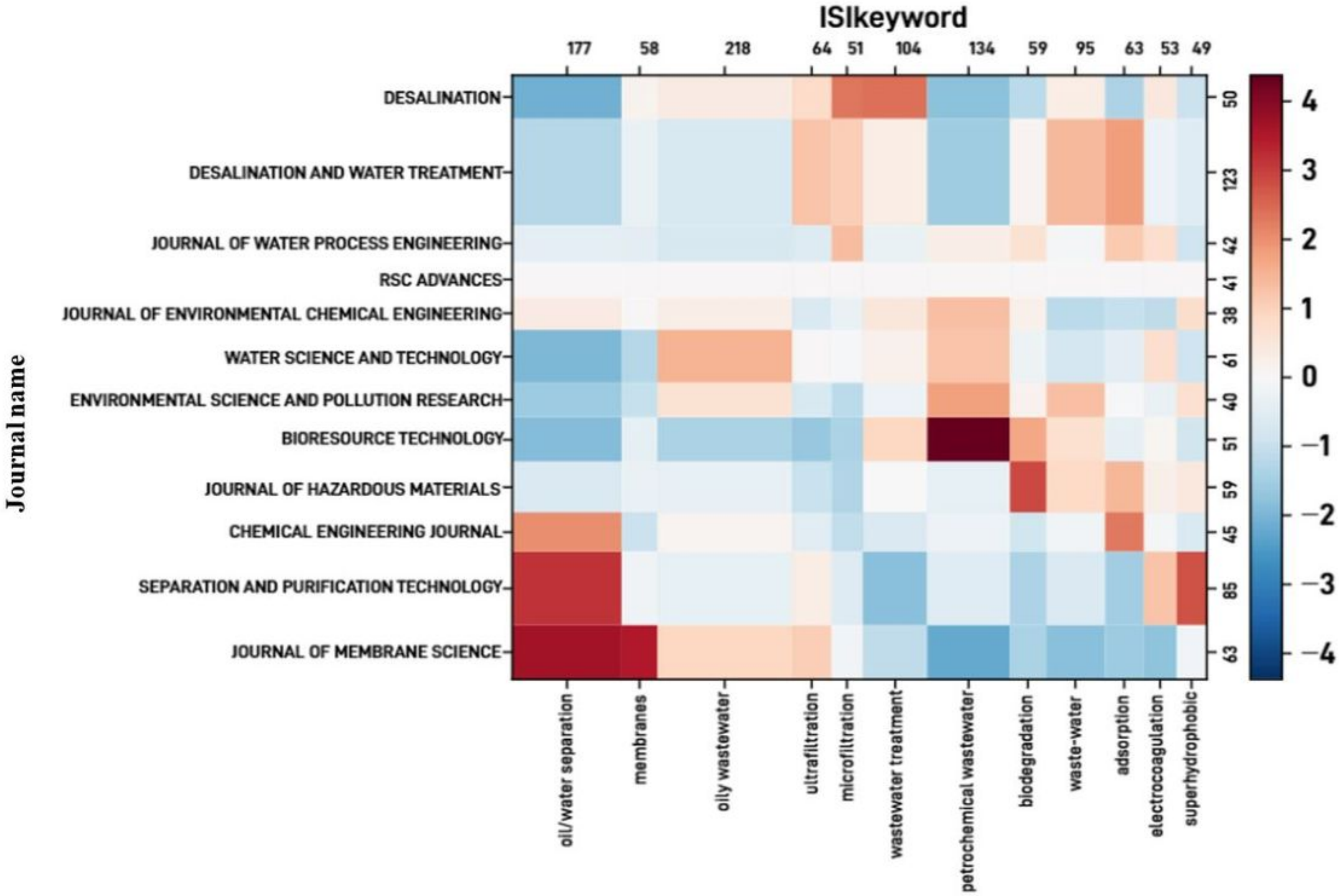

Figure 8

The contingency matrix between the keywords and journals based on web of science (WOS) by CorTexT manager.

Figure 9

The keyword semantic network based on web of science by CorTexT manager.

Figure 10

The bump graph on the keywords based on web of science by CorTexT manager.

Figure 11

The annual trend of keyword repentances in articles by using WoS (SCI-Expanded)

Supplementary Files

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- Table4.jpg