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Produced Water: An overview of treatment technologies

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Produced Water: An overview of treatment technologies

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Abstract

Produced water is one of the single most significant waste streams in the oil and gas industry, and because it is a residue of complex chemical composition, it can't be simply discarded in the environment, it should receive appropriate treatments before. This paper presents a mapping of the quantitative evolution, referring to the leading publications on the study of water produced with a focus on treatments. A bibliometric method was then adopted to build a structured database with the selected articles and then analyzed the number of publications, countries, areas of impact, authors, keywords, periodicals, and affiliations. The thematic has proved to be an essential line of research over the years. The analysis was considered in the period between 1969 and 2017. Several indicators were observed regarding the development of academic and technological research on water produced as well as its treatment processes. The study was performed in the Scopus database search engine to gather data, and 2434 documents were identified, with 851 articles investigated more specifically. This paper highlights the need for constant future studies about the produced water to minimize not only pollution but also reduce operating costs.

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1. Introduction

The oil industry has grown immensely, and, with this growth comes the environmental concern of disposing of the effluent produced by the industry. A typical oil reservoir usually contains oil, natural gas, and water. This water is known for produced water (PW), and it's one of the single most significant waste streams in the oil and gas industry [Sirivedhin and Dallbauman, 2004]. Generally, the ratio of oil and PW is 1:3 for most of the oil well [Munirasu et al., 2016]. The chemical composition of PW is complex. It includes a mixture of various components such as dispersed oil, dissolved hydrocarbons, organic acids, phenols, metals, as well as residues of chemical compounds added to the production line or separation [Utvik, 1999]. There is a wide variation in the level of composition of this water due to geological formation, the lifetime of the reservoir, and the type of hydrocarbon produced [Igunnu and Chen, 2012].

Without proper treatment, the final disposition of PW can pollute surfaces, groundwater, and soil. Therefore, these components need to have their concentrations reduced or completely removed using some type of treatment (chemical, physical, biological or a combination of these methods) so that oilfield produced water can be discarded at sea, reinjected into reservoirs or even use for irrigation [Ahmadun et al., 2009; Weschenfelder et al., 2016; Meneses et al., 2017; Al-Ghouti et al., 2019]. In order to minimize the environmental impact of PW disposal is necessary an effective treatment, which can be reached when different technologies are used together once the specialized literature affirms that sequential processes are more efficient with best results [Almarouf et al., 2015; Ebrahimi et al., 2010; Shamaei et al., 2018]. The legislation establishes rigorous criteria about the maximum permissible levels of contaminants like total oil-grease (TOG), salts, heavy metals, and certain chemicals, independent of the location for disposal. Several effluents with potential for environmental pollution are generated along the entire production chain [Ayotamuno et al., 2007, Pivel et al., 2009, Yana et al., 2010].

Thus, the purpose of this study was to quantitatively and qualitatively evaluate the scientific literature related to produced water and their treatment based on a bibliometrics analysis. This type of analysis has been used in the most diverse areas of research [Geng et al., 2017; Moro et al., 2018; Wang et al., 2018], as it provides results that can help researchers to select their potential research area better, recognize future academic collaborators, and identify journals and institutes that produce the most on the subject. A bibliometric analysis is also helpful to examine weaknesses and strengths, identify research gaps, and future research directions in one specific field.

2. Methodology

2.1 Methodologies and Data Sources

For this study, the Scopus database was used. The Scopus database, founded in 2004 by Elsevier, is one of the largest existing databases. Its library (or catalog) has more than 22,000 titles of papers besides having intelligent tools that can aid in bibliometric research. Also, Scopus has the option of exporting the information obtained from the literature in several formats. RIS (Research Information Systems) is one of the existing forms widely used in bibliometric analytical software. During bibliometric research, it is fundamental that the terms chosen are the most relevant ones; moreover, they should be searched in titles, summary, and keywords in the database (scientific articles). To avoid results that are not related to the subject, the leading search string was: TITLE-ABS-KEY ((("oilfield brine" OR "oilfield water" OR "oil field water" OR "oil-field water" OR "produced water") AND "treatment")) AND (LIMIT-TO (DOCTYPE, "ar")). A rigorous analysis was carried out in each scientific document found to verify its real integration within the thematic of the treatment of water produced.

2.2 Analysis tools

VOSviewer is an available computer program used for constructing and viewing bibliometric maps. In this study, it was used to visualize the network. This program also can be used to build maps of authors or journals based on co-citation data or to build maps of keywords based on co-occurrence data. VOSviewer also offers a tool that allows you to examine bibliometric maps in full detail [Van Eck and Waltman, 2010].

3. Results and Discussion

The initial search resulted in a total of 2434 documents which 1305 were scientific articles. The period corresponding to the research began with the first articles made available by the database until those made available in December 2017. Although the terms used have correctly restricted the search, articles were found that were not directly related to the topic addressed, such as those presented by Rashed et al. [2012], Beebe et al. [2015], and Mendez et al. [2011]. These unrelated articles were excluded from the obtained material. After a careful analysis of all the scientific documents, a total of 851 papers were selected and exported into RIS format for bibliometric analysis.

3.1 Number of publications by year

Figure 1 shows the distribution of the articles related to the PW treatment over the years. The first article related to this appeared in 1969 with the study of Kerver and Heilhecker [1969], which approaches to the use of inhibitors to prevent the deposition of calcium sulfate on rods and tubing.

Despite the fact that the first article found to be published at the late '60s, there was a higher growth of publications from the end of the 90's, with the most of these studies published between the years 2010 to 2017 (a period when 510 articles were published, representing 59.92% of the total). This result is explained by the interest of finding more efficient and economic forms of treatment to produced water. Even so, in the years 1970, 1972, and 1977 there were no publications in the Scopus database.

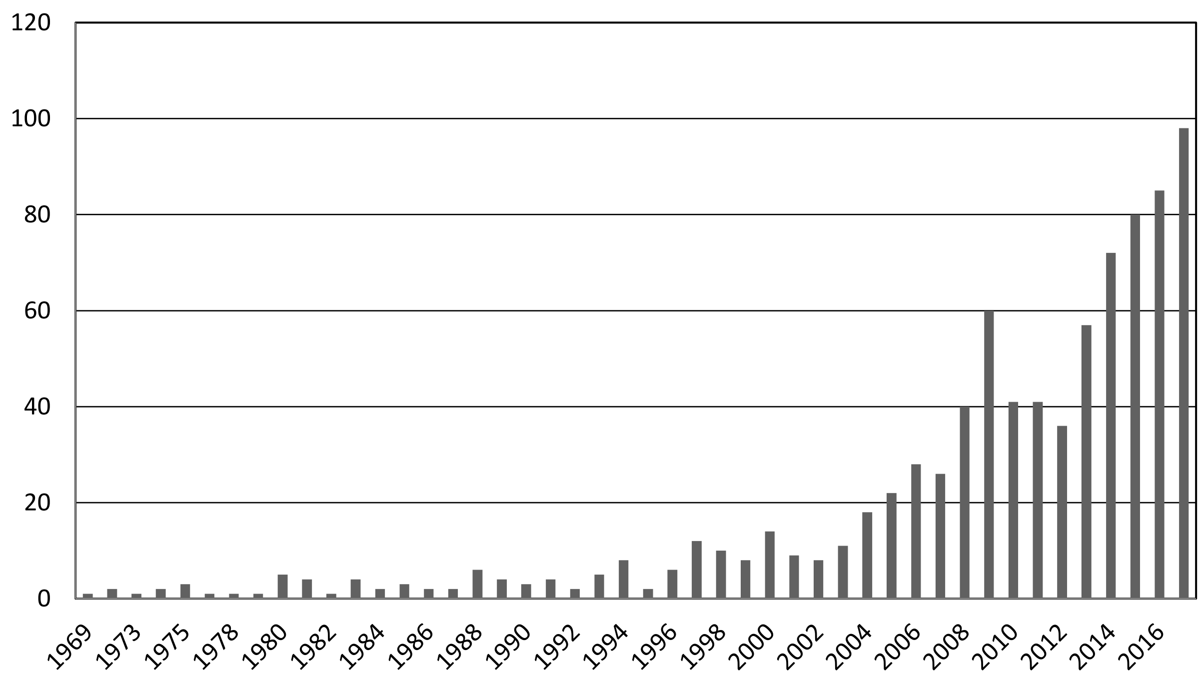


Figure 1. Number of publications by year about PW.

3.2 Countries/territories

From a world perspective, a total of 58 countries/territories published their papers about produced water, although 46,55% of them contributed with a maximum of two papers.

The existence of a small number of countries that dominate the publication of scientific documents was expected. As shown in Table 1, the ten most countries with more significant research development are responsible for 83.43% of all publications. The United States appears first with the most substantial amount of publications, followed by China and Brazil.

It's important to remember the categories are non-exclusive, and its document can be related to more than one country as a consequence of international collaborations.

Figure 2 shows the international collaboration between countries. Out of the total of 89 countries, 28 meet the threshold. The 20 countries with a higher number of partners were selected. According to the analysis, the United States is the country with the higher number of partnerships, 42, which were made with 14 different countries, followed by the United Kingdom with 26 and Canada with 25 collaborations.

Table 1. The top 10 most productive countries in PW.

Raking	Country	Documents	Percentage (%)
1	United States	221	25,97
2	China	216	25,38
3	Brazil	63	7,40
4	Canada	53	6,23
5	United Kingdom	35	4,11
6	Norway	34	3,99
7	Australia	29	3,41
8	Iran	24	2,82
9	Malaysia	20	2,35
10	South Korea	15	1,76

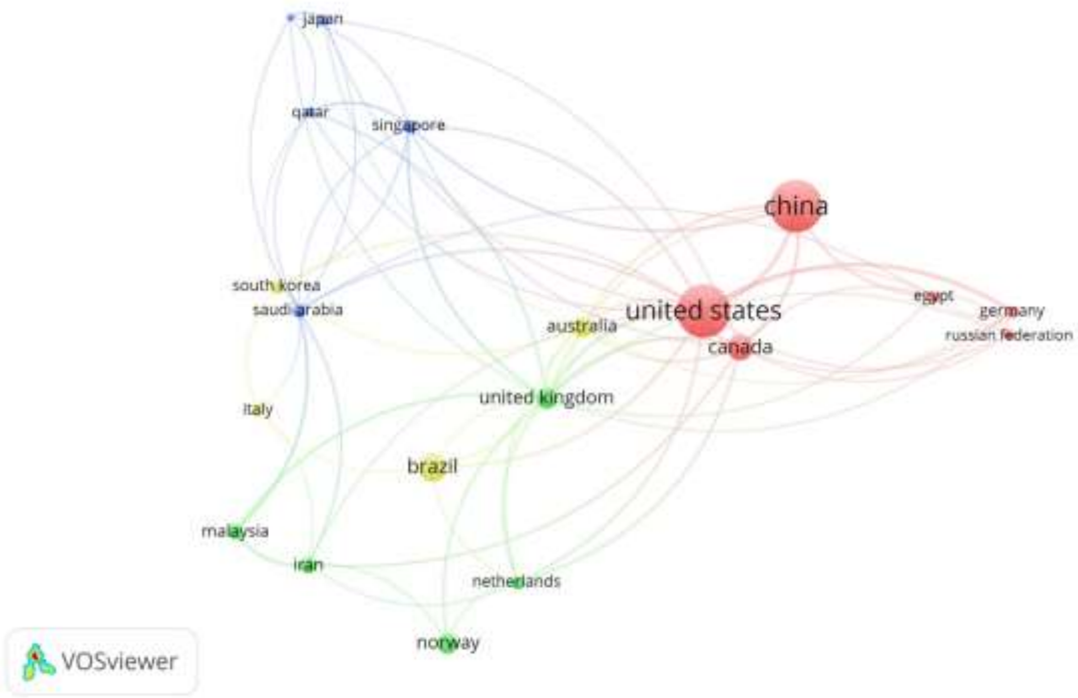


Figure 2. The international collaboration between countries, the minimum number of occurrences of documents, was set to 5. The volume of the circle in the map is the indicator of the contribution of the item (indicates the number of partnerships, the larger, the more that country had co-authorship), and the smaller the distance between two countries, the higher the relationship between them.

3.3 Subject area

According to Scopus, studies about the treatment of produced water involved 18 different academic disciplines. Figure 3 shows some of the strongest academics displaces found and the percentage by area. As can be seen, Environmental Science appears first with 42.3% of all publications. The most used journal in this research area was Desalination, and the country with the highest contributions in environmental science was United States (120 papers). The second more relevant area was Chemical Engineering (38.3%), followed by Energy (31.5%) and Chemistry (28.1%). Other areas, such as Engineering, Earth and Planetary Sciences, and Materials Science, also contributed to the development of PW related studies. This analysis does not rank the article in only one area, and it is worth remembering that an article can be linked to different areas at the same time.

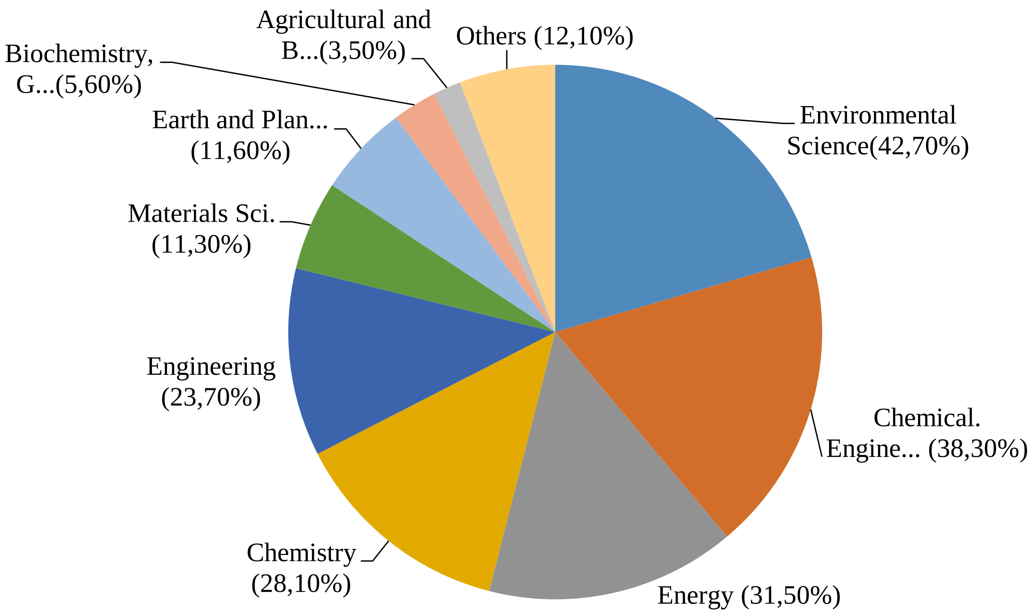


Figure 3. Areas involved in research about PW, as classified by Scopus.

3.4 Citation analysis

Among the bibliometric indicators to evaluate the quality of research, citation analysis is one of the most used ones. If an article is cited by another, this may indicate that its results possibly provide useful and valuable information to others. Therefore, it is credible to state that the more citations an article has, the more expressive it is.

In the present study, it was evaluated the top ten most cited articles related to the treatment of produced water, as Table 2 illustrates. For a better analysis of the scientific value of the articles, citations made from the own author's articles were disregarded in the count. Once more recent articles are not as popular as the older ones, so it was also considered for citation analysis, the number of citations per year (TC/Y). Thus, as observed, the most cited article was also what has more citations per year, and it was corresponding to the work entitled "Water management challenges associated with the production of shale gas by hydraulic fracturing" by Gregory et al. [2011]. This paper had the highest values of TC and TC/Y, showing an excellent value for the scientific area.

Another article entitled: "Produced water treatment by nanofiltration and reverse osmosis membranes" assumed the second most cited article position with 165 citations at the time of data analysis. In this paper, the authors test two nanofiltration and one low-pressure reverse osmosis membrane to treat the PW. The results showed that this treatment might be feasible depending on the quality of the water produced that wants to obtain [Mondal and Wickramasinghe, 2008]. Although the work of Mondal and Wickramasinghe [2008] occupies the second position in the total of citations, it has a low number of TC/Y (18.33) as also Mueller et al. [1997], Nicolaisen [2003], Tellez et al. [2002], Ji et al. [2002], and Deng et al. [2002] (Table 2).

Table 2. Top ten highly cited papers based on Total Citation (TC).
* citation per year (TC/Y): average number of yearly citations.

Ranking	Author	Journal	TC	TC/Y*
1	Gregory et al. [2011]	Elements	257	42.83
2	Mondal and Wickramasinghe [2008]	Journal of Membrane Science	165	18.33
3	Mueller et al. [1997]	Journal of Membrane Science	162	8.1
4	Warner et al. [2013]	Environmental Science & Technology	159	39.75
5	Nicolaisen [2003]	Desalination	121	8.64
6	Tellez et al. [2002]	Advances in Environmental Research	118	7.87
7	Coday et al. [2014]	Desalination	117	39.0
8	Hickenbottom et al. [2013]	Desalination	111	27.75
9	Dlugolecki and Van Der Wal [2013]	Environmental Science & Technology	94	23.50
10	Asatekin and Mayes [2009]	Environmental Science & Technology	92	11.50
11	Ji et al. [2002]	Ecological Engineering	91	6.07
12	Çakmakce et al. [2008]	Desalination	90	10.0
13	Ebrahimi et al. [2010]	Desalination	87	12.43
14	Ji et al. [2009]	Bioresource Technology	86	10.75
15	Deng et al. [2002]	Separation and Purification Technology	83	5.53

3.5 Author keywords

The author's keyword analysis is another topic of great interest because it can provide information on trends in a particular area of research [Li et al., 2009]. VOSviewer was used to visualize the most frequently used keywords. As a result of this analysis, the search returned a total number of 1818 keywords (Figure 4).
As expected, "produced water" appears as the most used keyword among the authors with a total of 238 occurrences and with 60 connections with different keywords followed by wastewater treatment (41 occurrences and 29 connections) and oilfield produced water (36 occurrences and 17 connections). Other keywords also appeared on the map, and they are related to different forms of treatment that represents a significant focus of research, such as desalination (19), adsorption (19), ultrafiltration (17), electrocoagulation (11), and flocculation (7).

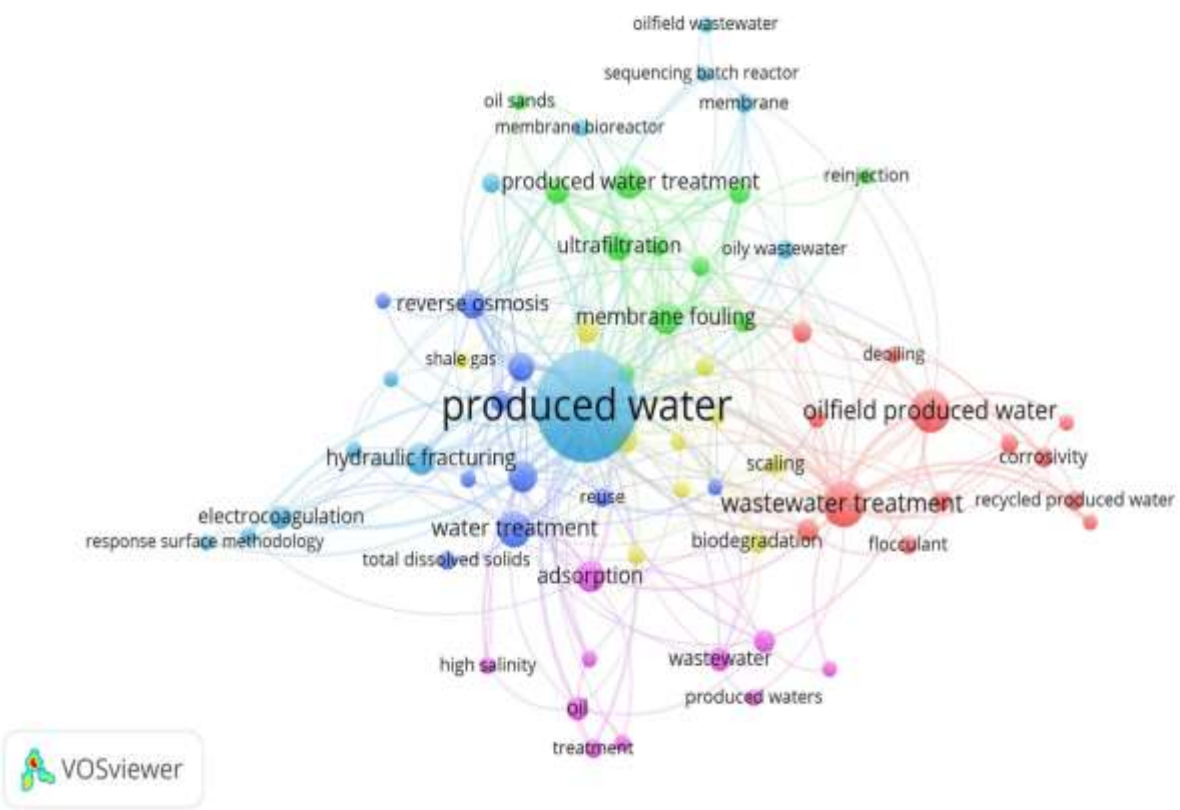


Figure 4. The network map of analysis of co-occurrence of author keywords, the minimum number of occurrences of a keyword was set to 5, of the 1818 keywords: 71 keywords meet the threshold.

3.6 Performance of journals

One hundred fifty-seven journals have published about produced water and treatment; of these, 46 ones (corresponding to 29.3%) contributed with only 1 article. Table 3 shows the top 10 journals (in terms of the total number of publications, TP) that most published on PW. Together, these journals contributed to more than 33% of the total publications.

Table 3. The top 10 most productive journals.

Raking	Journals	TP	%
1	Oilfield Chemistry	66	7.75
2	Desalination	42	4.93
3	Desalination and Water Treatment	38	4.46
4	Journal of Membrane Science	26	3.05
5	Oil & Gas Journal	22	2.58
6	Environmental Science & Technology	22	2.58
7	Separation and Purification Technology	19	2.23
8	Journal of Petroleum Science & Engineering	18	2.11
9	Word oil	17	1.99
10	Jpt Journal of petroleum technology	14	1.64

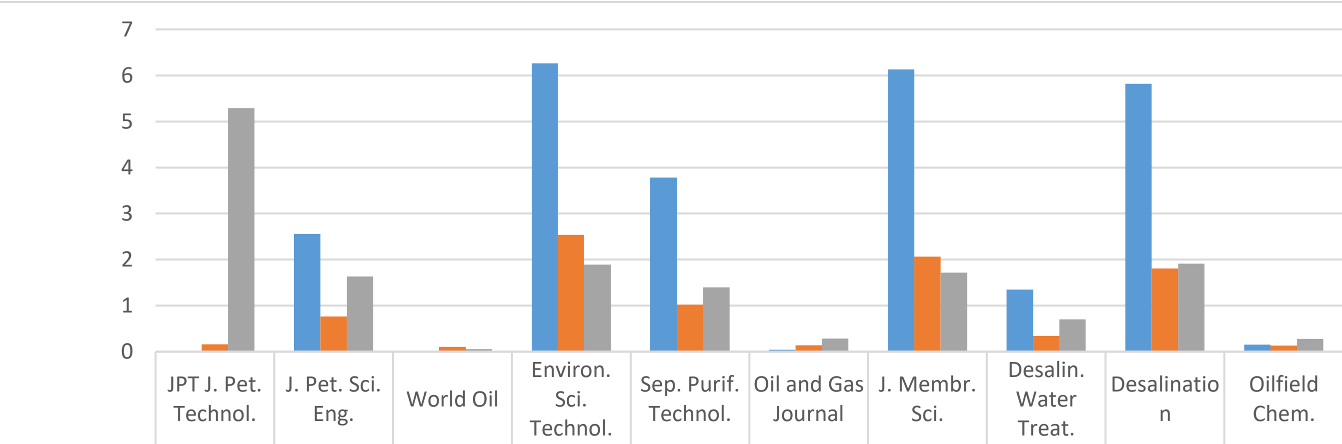
Oilfield Chemistry is the most influential journal with 66 publications on PW treatment, followed by Desalination (42 articles), Desalination and Water Treatment (38 articles), and Journal of Membrane Science (26 articles).

Other measures can also be used to evaluate the performance of a journal. Figure 5 shows the comparison between three commonly used indicators like Citescore, Scimago Journal Rank (SJR), and Source Normalized Impact per Paper (SNIP). While Citescore measures the average citations received per document published in this title; SJR is a measure similar to the impact factor (IF), but it does not consider all quotes equal and the prestige, quality, and reputation of the journal, which have a direct effect on the value of a citation. In its turn, SNIP is a factor that measures the impact of contextual citation by weighting citations based on the total number of citations in a subject field. Its value is calculated by dividing the number of citations received in a given year by the number of articles published in the journal during the three years above.

It is important to remember that different indicators offer different forms of evaluation, which, consequently, leads to different results. No indicator will provide the best result, so it is essential to use distinct ones to evaluate the performance of a journal better.

Figure 5 shows that, although Oilfield Chemistry has the most significant number of publications, it presents the lowest values of indicators, in addition to illustrating how they are related in some way to the number of citations and the quality of papers. Nevertheless, the articles published are not often cited in other articles, showing that it should not have an excellent indication for research. This fact can also be confirmed in Table 3, which shows the 15 most cited articles, but Oilfield Chemistry published none.

According to the indicators, the journals Environmental Science & Technology, Journal of Membrane Science, and Desalination are the most relevant among the scientific literature. In addition to their indexes are the largest, their publications are the most cited, according to Table 3.



	JPT J. Pet. Technol.	J. Pet. Sci. Eng.	World Oil	Environ. Sci. Technol.	Sep. Purif. Technol.	Oil and Gas Journal	J. Membr. Sci.	Desalin. Water Treat.	Desalination	Oilfield Chem.
Citescore		2.56	0.01	6.26	3.78	0.04	6.13	1.35	5.82	0.15
SJR	0.16	0.764	0.101	2.538	1.023	0.14	2.062	0.343	1.808	0.129
SNIP	5.292	1.631	0.057	1.889	1.394	0.288	1.72	0.702	1.911	0.28

Figure 5. Comparisons of Citescore, SJR, and SNIP scores for the year 2016 for the top ten productive journals on PW.

3.7 Affiliations

In total, 160 affiliations published on produced water and its treatments. Table 4 shows the 12 affiliations that had the most substantial amount published. As can be seen, the Federal University of Rio de Janeiro appears first followed by Petrobras (Petróleo Brasileiro S.A.), and both are located in Brazil. Analyzing Tables 1 and 4, it's possible to realize that these two affiliations are responsible for most publications (about 63%), showing that, in Brazil, the surveys related to water produced are more concentrated in these two organizations. According to Table 1, China appeared with 216 publications, and after, in Table 4, it seems as the country of origin of 7 of the 12 most productive affiliations, showing that it has several institutions researching about PW. The United States also deserves mention having two institutions among the list.

Table 4. The top 12 most productive affiliations/organizations.

Ranking	Affiliation	Documents	Country
1	Universidade Federal do Rio de Janeiro	22	Brazil
2	Petrobras	18	Brazil
3	Chinese Academy of Sciences	18	China
4	Ministry of Education China	16	China
5	Daqing Petroleum Institute	16	China
6	Colorado School of Mines	16	EUA
7	Clemson University	16	EUA
8	China University of Petroleum East China	16	China
9	University of Calgary	15	Canadá
10	Shengli Oilfield Company	15	China
11	Harbin Institute of Technology	14	China
12	Southwest Petroleum University China	13	China

3.8 Types of Treatment

Of the 851 articles related to PW, about 55% of them address some type of treatment, which were classified as physical, chemical, biological, membrane treatment, combined systems, and undefined. Figure 6 shows the percentage of each classification adopted. The articles that were classified as undefined correspond to those that were not possible to identify by a less complicated analysis of the type of treatment used.

It is important to remember that no treatment alone will leave the produced water in the parameters established by the legislation due to a large number of different components present in the composition of the water samples. The chosen treatment process will depend on some factors as capital costs, operating expenses, and waste streams, for example [Arthur et al., 2005].

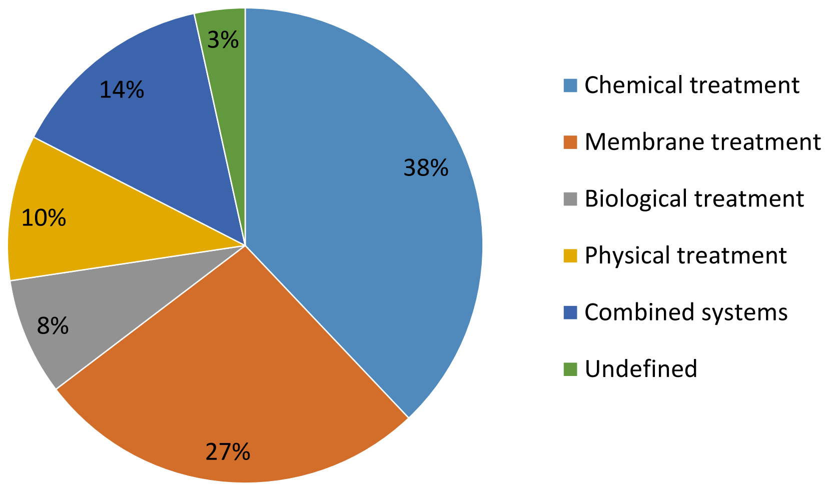


Figure 6. Classification of the articles related to the produced water address some type of treatment, which was separated from the method used to purify the PW.

3.8.1 Chemical treatment

3.8.1.1 Chemical Precipitation

Coagulation and Flocculation are treatments used to remove colloidal and suspended particles but are not effective treatments to remove dissolved components. In a study of the total suspended solids (TSS) from a real produced water, ferric chloride and aluminum sulfate were used as alternative coagulants, and the cationic and anionic polyelectrolyte were used as flocculants in different doses. As a result, the use of aluminum sulfate and cationic polyelectrolyte (DF 492) showed a better performance in TSS removal [Roccaro et al., 2014]. Another study, using alum and ferric chloride, evaluated coagulants for clarification and removal of boron; high doses were used to remove about 80% of the boron, which makes the boron removal process unfeasible [Chorge et al., 2017].

3.8.1.2 Treatment with ozone

Ozone treatment is a process that effectively reduces petroleum hydrocarbons [Chip and Tittlebaum, 1995]. One study used the new ozonation technique coupled with sand filtration to remove oil from water rapidly. This technique incorporates rapid, successive cycles of compression and decompression during ozonation. The parameters evaluated were changes in turbidity, COD, BOD, and sheen presence following treatment. This technique proved to be quite useful because it reduced the established parameters in a way that the water could be disposed of in a safe way to the environment or reused [Cha et al., 2010].

3.8.1.3 Fenton process

Fenton technology is a promising and alternative method for wastewater treatment, using hydrogen peroxide as oxidant and ferrous ions as a catalyst [Huang et al., 2017]. Li et al. [2016] investigated the removal efficiency of BTEX (benzene, toluene, ethylbenzene, and isomers of xylene) using Fenton's reaction and electrolytic oxidation. The results obtained revealed a BTEX removal higher than 95% at pH 4. Moraes et al. [2004] used a photo-Fenton process to the treatment of the saline wastewater contaminated with hydrocarbons. Li et al. [2016] used a cathode Fenton reactor for treating oil-produced water to reduce toxicity and improve biodegradability, resulting in a successful treatment. The COD removal rate was 78.4 %, while the oil rate was 89.6%.

3.8.1.4 Electrochemical process

Ezechi et al. [2015] studied the removal of boron from the water produced by electrocoagulation. By using an iron electrode, the removal efficiency was 97.6% under optimal conditions applied. Gargouri et al. [2014] used electrochemical technology for removing petroleum hydrocarbons from produced water using lead dioxide and boron-doped diamond electrodes. The results were satisfactory, but the energy consumption and process time make useless anodic oxidation for the complete elimination of pollutants from produced water.

3.8.2 Physical treatment

3.8.2.1 Hydrocyclones

Hydrocyclones are equipment used for solid-liquid or liquid-liquid separation. In oil extraction, the water produced usually contains solids. These solids are from reservoir origin and are usually covered with a thin layer of oil [Lohne, 1994]. Some studies have been found on the use of hydrocyclones such as Kharoua et al. [2010], who evaluated the parameters that affect the performance of de-oiling hydrocyclones; and Angelim et al. [2017] who applied computational fluid dynamics (CFD) in the analysis of hydrocyclone as a pretreatment for the removal of oil from PW.

3.8.2.2 Adsorption

Several studies have sought an alternative and cheaper raw materials such as olive leaves powder (OLP), eggplant peel powder (EPP), and coconut pith (CP) to be used as adsorbents in the removal of oil and metals [Ibrahim et al., 2017, Gulistan et al., 2016, Ibrahim et al., 2016 and Saman et al., 2016]. Other studies looked for new adsorbents that remove some specific compounds such as Costa et al. [2012] who investigated the potentials of peat and angico hardwood sawdust to remove BTEX; and Shi et al. [2017] who evaluated the feasibility of using nanostructured δ-Bi2O3 to remove bromide from PW. The results of this study revealed that δ-Bi_2O_3 could be used to remove bromide from water solutions that have a low concentration of chloride.

3.8.3 Membrane treatment

About 27% of the treatments found comprise membrane separation processes such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). Among them, MF can be operated in two forms, direct flow or crossflow. Chen et al. [1991] used ceramic crossflow microfiltration to remove oil, grease, and suspended solids from produced water. Zhang et al. [2016] used a polytetrafluoroethylene (PTFE) microfiltration membrane to treat oilfield water produced, and the efficiency of the treatment was enough to meet the standards of water quality reinjected in China.

Making a comparison, UF has more advantages over other methods for treating oily wastewater due to its high oil removal efficiency, chemical additives, low energy costs, and small space requirements (He and Jiang, 2008). Reyhani et al. [2013] and Zoubeik et al. [2017] used the Taguchi approach, which aims to optimize a process, to evaluate the performance of a UF membrane. The former one utilized a polymer membrane while the second one used a silicon carbide (SiC) membrane, but both types of research obtained favorable results. NF membranes are generally designed to be selective for multivalent ions rather than univalent ions [Ahmadun et al., 2009]. Pages et al. [2013] studied this selectivity of ion rejection theoretically and experimentally. He found that rejection crucially depends on their environment. RO is a widely used process for the total removal of dissolved solids. Several researchers used this type of treatment, such as Melo et al. [2010] and Le [2017], who studied the use of RO to desalinate PW to be reused in irrigation or other beneficial forms.

3.8.4 Biological treatment

Aerobic and anaerobic microorganisms have been studied to treat PW biologically. This type of treatment is generally regarded as the most cost-effective method for organics removal [Janson et al., 2015]. In these treatments, it’s important to control the presence of salts in PW once it may end up inhibiting the biological process [Sharghi et al., 2013].

Tellez et al. [2005] used an activated sludge system to remove hydrocarbons from PW, obtaining a removal efficiency of 99% at a produced water flow rate of 1890 L/day and a mean cell residence time of 20 days.

Pendashteh et al. [2010] studied the efficiency of a sequential batch reactor (SBR) to remove hydrocarbon compounds in samples of real and synthetic produced water. The reactor was inoculated with isolated tropical halophilic microorganisms capable of degrading crude oil. The results obtained with synthetic water varied according to the salt content present since the real water produced showed that the removal rates of the main pollutants from wastewater, such as COD, TOC, and OG, were above 81%, 83%, and 85%, respectively.

Paz et al. [2012] studied the efficiency of removal sulfides and phenols from oil field produced water (OPW). The experimental design consisted of two FSFCW (FSFCW I and FSFCW II) with gravel and soil (as media) and emergent aquatic plants. *Cyperus luzulae* and *Cyperus ligularia* were planted in FSFCW I while *Cyperus feraz* L, *Paspalum* sp., and *Typha dominguensis* were planted in FSFCW II. In both cases, aquatic plants did not perform a good removal of the compounds from the water produced.

In another research, the changes in the profile of a microbial community used to remove ammonia from the produced water were evaluated when subjected to a gradual salt increase (NaCl), and the complete inhibition of the removal occurred at 125 g/L NaCl [Quartaroli et al., 2017].

4. Conclusion

It can be observed an increase in the quantities of publications about the treatment of produced water around the world, which can be attributed to (i) an environmental concern by imposing legislation on the disposal of produced water and (ii) an increase in the quantity generated due to the maturation of the oil reservoirs. Currently, ten countries with the most extensive development in PW researches are responsible for more than 80% of the publications. Besides, 30% of the publications direct information relevant to the scientific and technological community.

One hundred fifty-seven journals have published about produced water, but according to the indicators, the journals Environmental Science & Technology, Journal of Membrane Science, and Desalination were the most appropriates.

Physical, chemical, biological, and combined treatments were adopted as technologies to investigate and minimize contaminants of the PW. As previously stated, no treatment alone leaves the water produced in the standards for disposal or reuse. The best choice of the combination will be one that does not pollute the environment and is not too expensive for the industry.

There was no doubt that this type of study based on massive data can reveal the macrostate of the development of the field and still serve as a base for future investigations into the identification of influential authors, journals, works, institutions, and subjects in the field of produced water and treatment.

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