Produced Water Treatment: A Bibliometric Review of Strategies and Technologies

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Produced Water (PW) contains chemical compounds and heavy metals that make it toxic and harmful to ecosystems and human health. The inadequate disposal of this byproduct, which is the largest in the oil industry, can pollute water bodies, impact biodiversity, and harm communities that depend on water for consumption and agriculture. This work analyzed the most widely used technologies and strategies for PW treatment. The bibliometric research was based on the Web of Science platform. It mapped the main approaches in the last five years, identifying three essential groups of treatment: physical, chemical, and biological, with increasing interest in the latter. The study emphasizes the importance of enhancing PW management to mitigate environmental impacts and promote more sustainable solutions.
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The unit operations related to oil production and extraction processes generate, in addition to the central processing objective, byproducts and effluents that, unlike crude oil, do not have high added value and must be disposed of in a way that does not affect or minimally impacts the environment [1].

Produced Water (PW) is the water that reaches the surface along with crude oil and is considered the most significant byproduct of the oil industry. It is generated in large volumes, with a global ratio of 3 barrels of PW for 1 barrel of oil. The composition of PW varies according to the maturity and region of the producing well. It is complex, containing dissolved and dispersed oil compounds, production chemicals, dissolved gases, dissolved formation minerals, and production solids, which include formation solids, corrosion, scaling products, asphaltenes, waxes, and bacteria. Due to its high salinity and toxicity, the reuse and disposal of this material without prior treatment are prohibited [1,2].

In this context, physical, chemical, and biological treatments are adopted to reduce the level of hazard associated with this byproduct. The choice of the ideal technology depends on the intended destination of the PW (disposal and reinjection are the most common), production base location, equipment and infrastructure availability, technical feasibility, costs, and legislation [1]. In Brazil, CONAMA Resolution 393/2007 specifies the required standards for managing this byproduct. The objective of this work was to map, through a bibliometric review, the main treatments applied to produced water, in addition to presenting the microbial pathway as a sustainable treatment possibility that may enable safe reuse.

Materials and Methods

The study was conducted through bibliometric analysis to map the main techniques and strategies used in the last 5 years to treat Produced Water. The database used was Web of Science, with the keywords “produced water” in the title and “treatment” and “technologies” in the abstract. The Boolean operator AND was used to delimit the results obtained.

The results were subjected to a primary evaluation of the titles to verify their correlation with the proposed theme. After reading the titles, the conclusions were analyzed to understand the treatment specifications. Open-access filters were not applied, and the focus consisted of articles, regardless of whether they were reviews or not.

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The retrieved documents from the search were analyzed using VOSviewer software version 1.6.20, which involved keyword co-occurrence and the removal of non-related terms, resulting in a network of clusters. A chart was also created to succinctly highlight the treatments and facilitate the understanding of the bibliometric review.

Results and Discussion

The search through the Web of Science database yielded 113 documents analyzed using VOSviewer software, with a minimum of four co-occurrences. From the 61 results obtained, non-related keywords were removed. The software displayed 3 clusters, illustrated in Figure 1, showing the intrinsic correlation among studies published in various countries. This demonstrates that advancements in the development of more sustainable and effective technologies and strategies are of global interest.

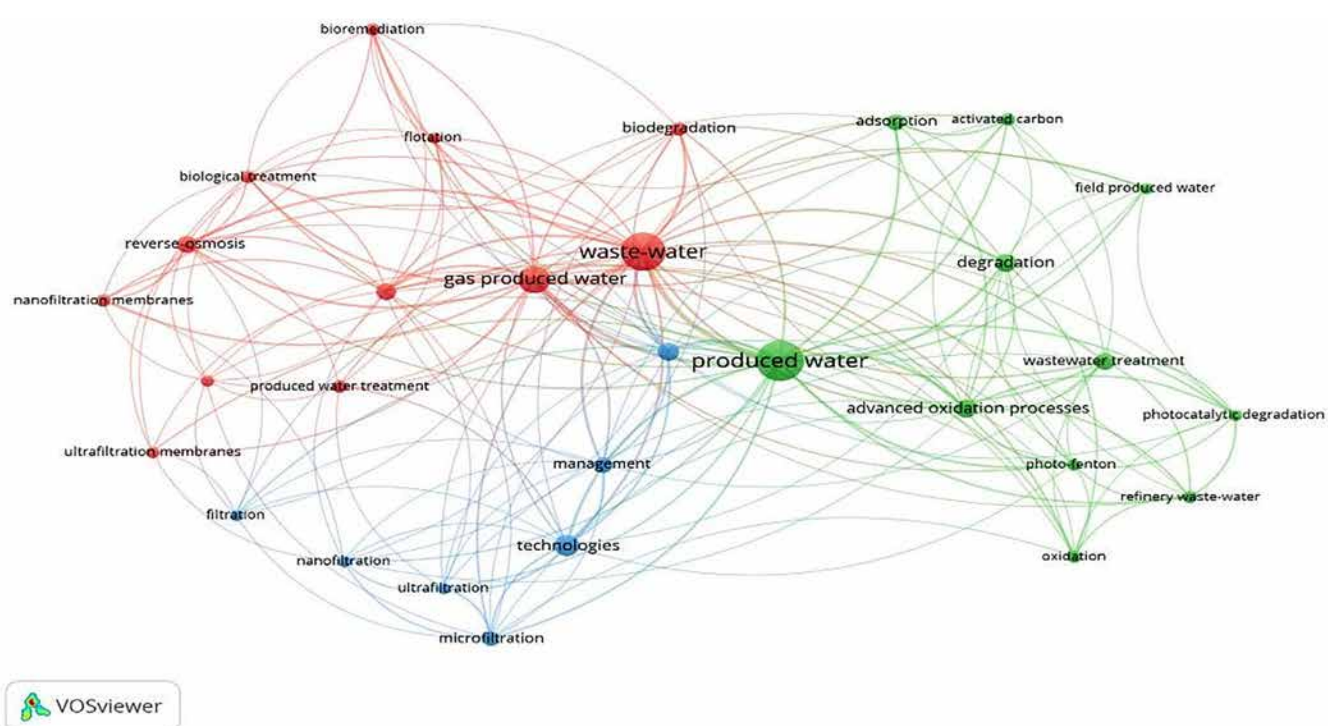
The blue cluster exhibits 7 correspondences to physical treatments, with a particular emphasis on filtration. The red cluster, comprising 12 items, highlights the predominance of physical treatments and the growth of biological processes.

The green cluster attributes greater relevance to chemical treatment processes, with emphasis on oxidation and adsorption. Box 1 presents the most studied treatments, highlighting their key features, nature, and limitations.

Membrane systems demonstrated significant competence in the primary treatment of PW, removing suspended solid contaminants in a compact design; however, it is necessary to overcome the challenges of membrane fouling to enable large-scale use [3]. Secondary treatment aims to remove emulsified oil, and flotation stands out by minimizing the environmental impacts of chemical compounds. Efficiency depends on pH and the probabilities of collision, adhesion, and stabilization of oil droplet bubbles. Future research is needed to analyze intervening factors to optimize this process [4].

Hydrocyclones are an efficient, compact, and durable technology with good cost-effectiveness. Their principle is the separation of layers according

Figure 1. Cluster network through keywords.



Box 1. Summary of treatments applied to produced water.

Treatment Types	Examples	Removal Efficiency	Limitation	References
Physical	Membranes	Suspended solids	Easy membrane fouling	[3]
	Flotation	Oil droplets	Long retention period	[4]
	Hydrocyclones	Up to 98% of oil without pre-treatment	Unstable flow in single-entry models	[5]
Chemical	Oxidation	Dissolved oil at low concentrations	Requires intensive monitoring	[6]
	Adsorption	Dispersed and dissolved oil	Reduced efficiency at high contaminant concentrations	[6]
Biological	Bioremediation	Organic compounds by bacteria	Adjustment of C, N, and nutrient sources	[7]
	Phytoremediation	Organic compounds by microalgae	Requires pre-treatment	[8]

to density, and their effectiveness in oil-water separation depends on inlet flow rate, velocity, and oil droplet size. Dual-entry models are more efficient, but the impact of turbulence on particles requires further study [5].

Oxidation facilitates the removal of organic and inorganic compounds, necessitating periodic calibration. Adsorption is effective in PW treatment, as it reduces BTEX and up to 80% of heavy metals. Both are independent of total dissolved solids concentrations and salinity; however, a disposal system is necessary for the waste generated by adsorbent consumption [6].

PW contains nutrients that favor the development of degrading microalgae, as well as indigenous microorganisms that act in the bioremediation of alkanes and aromatic hydrocarbons. Biological processes aim to safely reuse PW and require monitoring and pre-treatment, particularly in the case of phytoremediation [7,8].

Conclusion

The increase in oil production and growing environmental concerns reinforce the need to improve PW management. Treatments can be applied individually or in an integrated manner, the latter being highlighted in the literature as more efficient, since it removes different degrees of distinct compounds. Physical processes, such as membranes, flotation, and hydrocyclones, are widely used in primary treatment. In contrast, chemical processes, including oxidation and adsorption, perform better when integrated with physical treatments, as they require coupled waste disposal systems. Biological processes are emerging as promising alternatives, which may utilize native or induced microorganisms, in the case of phytoremediation, to reduce the hazardous level of this effluent, while also enabling its safe reuse, including as an input for the industrial sector. Besides contributing to environmental preservation, these strategies drive the circular economy and sustainable development.

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