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Review

Navigating Produced Water Sustainability in the Oil and Gas Sector: A Critical Review of Reuse Challenges, Treatment Technologies, and Prospects Ahead

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Abstract: The petroleum industry produces a large amount of wastewater, known as produced water (PW), during oil production and processing. This PW contains hazardous organic and inorganic components that can harm the environment. Conventional treatment methods have been used to purify PW, but they do not meet environmental regulations, especially when the goal is to reuse the water. Therefore, further research is needed to find an effective technology for managing PW. This review focuses on the characteristics and management of PW originating from oil and gas fields. Firstly, we provide a detailed overview of PW production scenarios worldwide and in the US with detailed quantities and chemical compositions of organic, inorganic, and physicochemical characteristics. Secondly, challenges and environmental concerns associated with treating PW are discussed. Thirdly, all relevant treatment technologies for PW are systematically explored. In addition, this review highlights the management of PW and suggests treatment options and best practices for the industry, and finally, future research needs and opportunities for sustainable water treatment and effective reuse technologies are addressed. Because PW contains a variety of severe contaminants, single methods have not been effective in converting it to a reusable form or fulfilling disposal criteria. As a result, integrated technologies may provide a potential approach that not only meets regulatory standards but also provides chances to employ PW as a non-conventional water supply. Advances in PW management are critical and demand a defined framework and risk-based approach to determine and build the most efficient plan.

Keywords: produced water; organic and inorganic components; physicochemical characteristics; hybrid treatment; treatment technologies

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1. Introduction

Oilfield produced water (PW) is the industry's principal source of waste byproducts [1–3]. Oil-producing countries, especially those with limited water resources, face significant difficulty in treating PW for recovery and reuse [4–6]. Depending on its quality and content, PW can be treated using a variety of technologies. Numerous nations are currently undertaking substantial endeavors to ascertain efficacious and cost-effective treatment methodologies in order to rehabilitate their freshwater supplies. The compositions of pollutants play a major role in the selection of acceptable methods. According to the degree of contamination and the requirement for water quality, several treatment strategies can, therefore, be used. To successfully remove pollutants and/or lessen their detrimental effects on the environment, methods comprising physical, chemical, biological, and membrane treatments have been applied [7].

In general, a single treatment strategy cannot meet every reuse and disposal requirement. Physical treatment methods are unable to comply with the regulatory restrictions for oilfield produced water (PW) due to the presence of highly hazardous contaminants, such as phenols, radionuclides, and other persistent organic pollutants [8,9]. In addition, flocculation and coagulation, two chemical treatment procedures, have not been shown to be efficient enough to remove dissolved elements. Sludge generated from chemical treatment operations also contributes to effluent's concentration of dangerous metals [8–10]. While membrane treatment is effective, it does have certain limitations, such as its sensitivity to feed-stream constituents, periodic cleaning, disposal and recycling issues, and the requirement for further waste treatment during the backwash process [11–13]. Numerous studies in recent years have identified process integration as a viable strategy for treating and recycling PW [8,9,14–18].

Therefore, in this detailed study, we first examine oilfield PW, its origins, its characteristics, and the regulations governing its disposal. The pros and cons of the various treatment technologies and hybrid systems now in use for oilfield PW management are then explored at length. Finally, a conclusion and future prospects are provided.

2. Overview of Produced Water in Oil and Gas Industry

The extraction of oil and gas supplies from shale has become feasible due to the use of horizontal drilling and hydraulic fracturing techniques [19,20]. Hydraulic fracturing is the most popular technique for recovering unconventional gas and tight oil from shale [21]. However, the exploration and production of oil and gas generates a significant amount of solid, liquid, and gas waste, with liquid waste comprising the majority [22]. Water is the main liquid effluent from oil and gas exploration activities [23].

Produced water, which is composed of various organic and inorganic materials, has gained attention due to its impact on the environment [8,24,25]. The water footprint of oil and gas production, particularly in unconventional gas and tight oil recovery, has also been a focus of recent research [26,27]. The management of flowback and produced water (FPW) from shale oil and gas (SOG) exploration is a critical issue for both economic and environmental reasons [19,28]. Different techniques are used to manage extracted water, including disposal, reinjection, and recycling.

Currently, disposal accounts for 46% of produced water in the United States, followed by reinjection at 41% and recycling at 13% (Figure 1). However, with the expected increase in the water-to-oil ratio for crude oil resources by 2025, the market for purifying and utilizing produced water is likely to expand significantly [29,30]. The water-to-oil ratio is expected to increase by 2025, leading to a growing market for purifying and utilizing produced water [31].

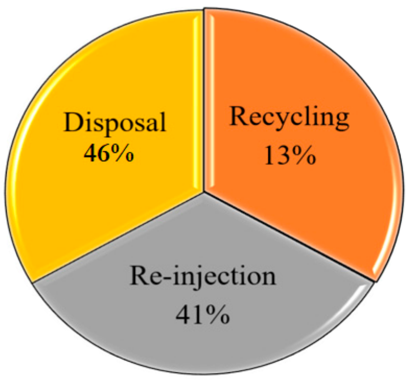

Figure 1. Produced water scenarios in oil and gas industry (data from [29,30]).

Produced water in the gas industry is a combination of condensed and formation water, as water injection is not used [32]. Compared to oilfields, produced water from gas fields is more acidic and volatile [32]. The onshore oil and gas industry disposes of produced water through the subsurface, while the offshore industry directly dumps it into the aquatic environment, causing harm to marine ecology [32]. The composition of produced water is influenced by geological and geographical factors of the reservoir and the type of hydrocarbon formation [32]. In shale oil and gas production, produced water includes flowback water and formation water [19]. The flowback water rate during well extraction initially increases and then decreases over time. Figure 2 shows the main sources of produced water, such as reservoir formation water, flowback water, and conventional and unconventional oil and gas production.

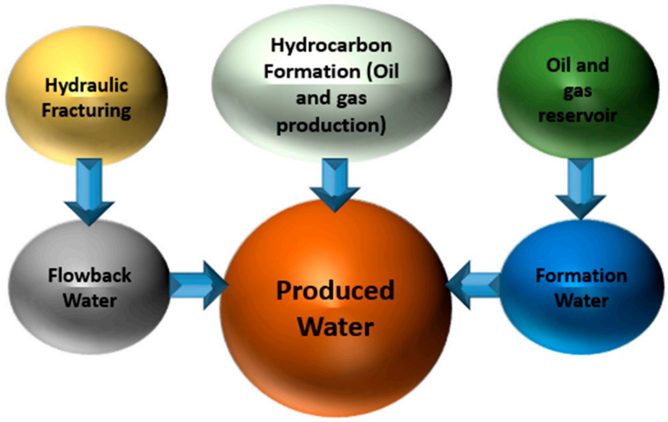

Figure 2. Different sources of produced water.

The volume of produced water from oil or natural gas production varies based on location and extraction method [33–36]. Produced water contains radioactive elements, salts, metals, and hydrocarbons [33–36]. The physical and chemical qualities of produced water also vary based on geographic location, geologic formation, and type of hydrocarbon product [37,38]. Reservoir fluid, in addition to oil, gas, and water, contains other components. When reservoir fluids are separated during the oil production process, the pressure drop leads to the formation of carbonate ions and the release of carbon dioxide. If the produced water is discharged into the sea or other bodies of water, it can contain dissolved hydrocarbons, heavy metals, CO_2 gas, residual oil, and water-soluble compounds, making it harmful to the environment. Water treatment is necessary to mitigate these effects [39]. Figure 3 illustrates the water sources used in oil and gas exploration.

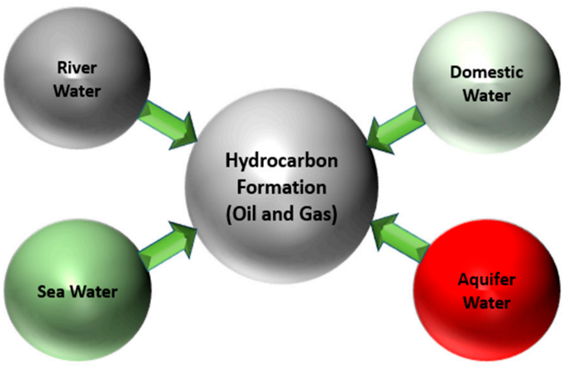

Figure 3. Water injection sources for hydrocarbon formation.

The United States, Russia, and Saudi Arabia are the world's three largest producers in terms of crude oil output. The United States has nearly one million wells that produce approximately 3.8 billion cubic meters of produced water annually [40–43]. Russia's annual oil equivalent production of 285 million metric tons results in a production of 1.5 billion cubic meters of produced water [43,44].

According to Figure 4a, the volume of produced water generated in 2017 and 2018 by the United States, Russia, and Saudi Arabia, the three largest oil and gas-producing nations, is compared. Additionally, Figure 4b includes data from Brazil and Oman, allowing for a comparison of their 2018 output as well.

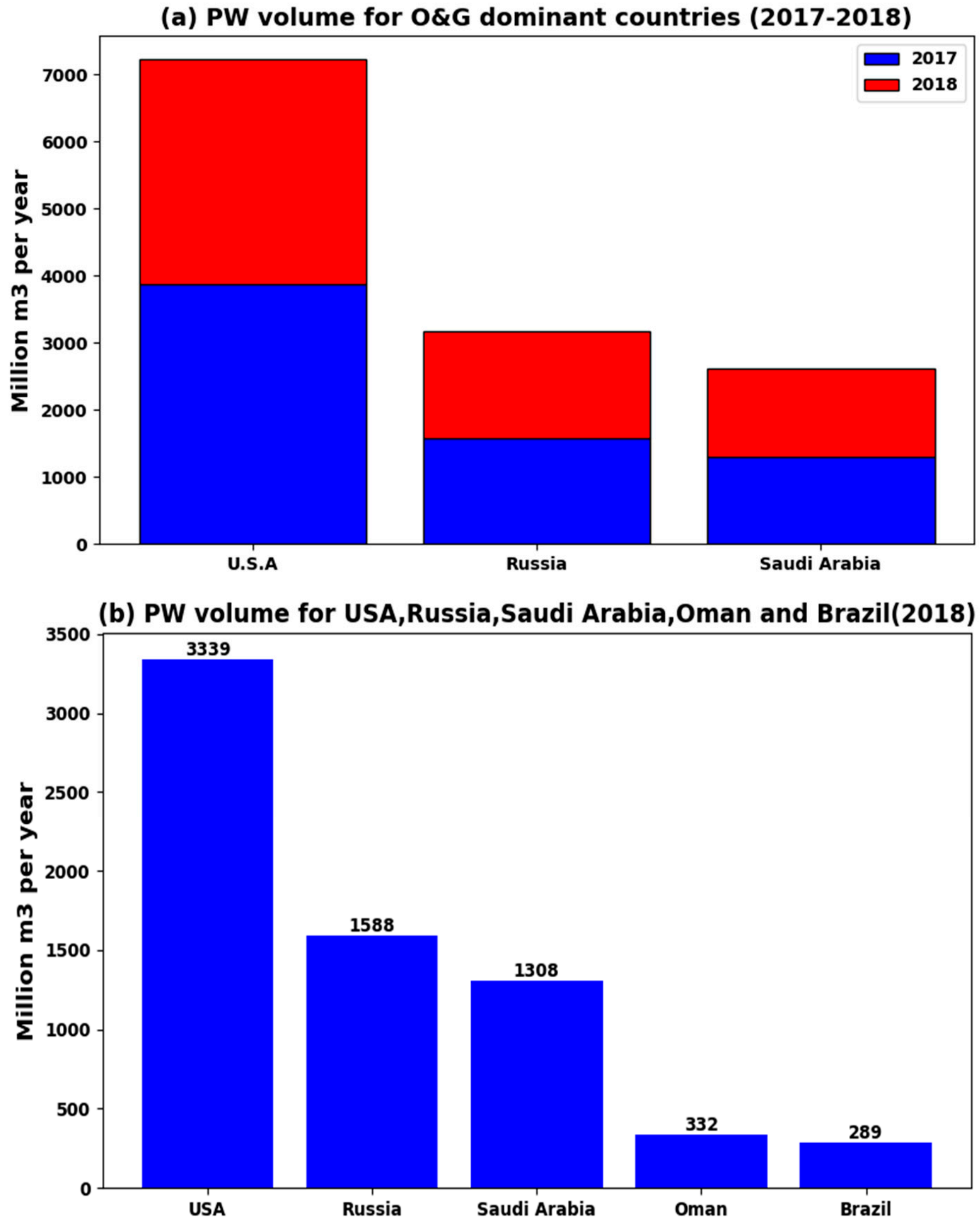

Figure 4. (**a**) PW volume for dominant oil- and gas-producing countries (USA, Russia, and Saudi Arabia) for 2017 and 2018; (**b**) PW volume for USA, Russia, Saudi Arabia, Oman, and Brazil in 2018 (data from [42–49]).

From 2012 to 2017, oil production in the US increased by 50.4% to 3.4 billion barrels per day, a 94% increase from 2007–2017 (Figure 5). Texas was the leading producer, accounting for 37% of hydrocarbon production. The federal offshore enterprise was the second largest hydrocarbon producer. North Dakota produced 11% of crude oil in 2017. Alaska, New Mexico, California, Oklahoma, Colorado, Wyoming, and Louisiana were among the top ten oil-producing states in 2017 [42].

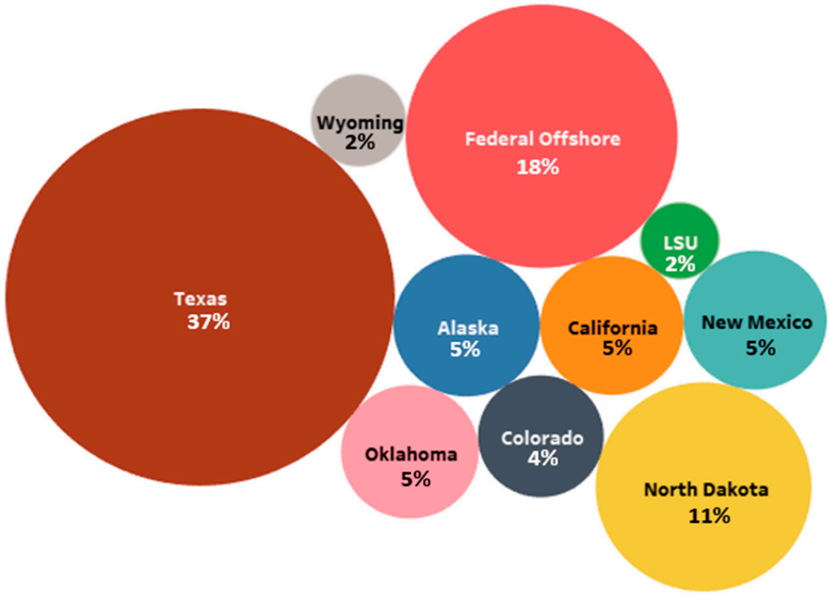

Figure 5. Top ten oil-producing states in the US. (data from [42]).

According to Figure 6, Texas was the leading producer of natural gas in the United States in 2017, accounting for 23.0% of the total output. Pennsylvania followed in second place with a proportion of approximately 16%. Louisiana and Alaska both contributed 9% each, while Oklahoma and Colorado contributed 7% and 6%, respectively. New Mexico produced more natural gas than Wyoming, Ohio, and West Virginia combined, with a 5% share compared to their combined 4%. According to John Veil's report in 2020, gas production in the United States experienced a significant increase of 17.7% from 2012 to 2017, reaching a total of 35 billion Mmcf [42].

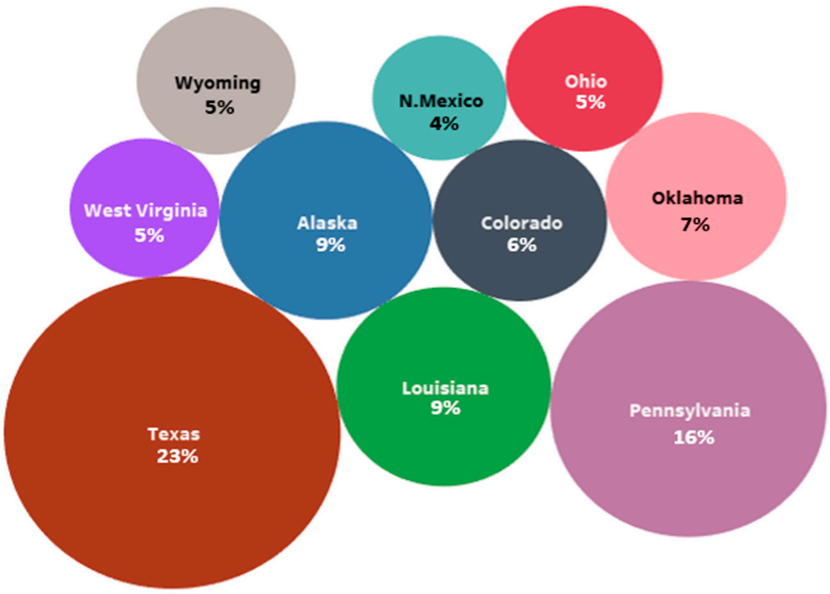

Figure 6. Top ten gas-producing states in the US (data from [42]).

In 2017, 24.4 billion barrels of water were produced from oil and gas production, equivalent to one trillion gallons of water annually. This represents a 15.2% increase from 2012 and a 16.2% increase from 2007 to 2017 as shown in Figure 7. The top ten states in the US in terms of generated water production in 2017 include Texas, which contributed to the highest discharge (41% in 2017), followed by California and Oklahoma, North Dakota, Wyoming, Kansas, Louisiana, New Mexico, Alaska, and the federal offshore. The volume of produced water has increased by 16.2% in the past decade [42].

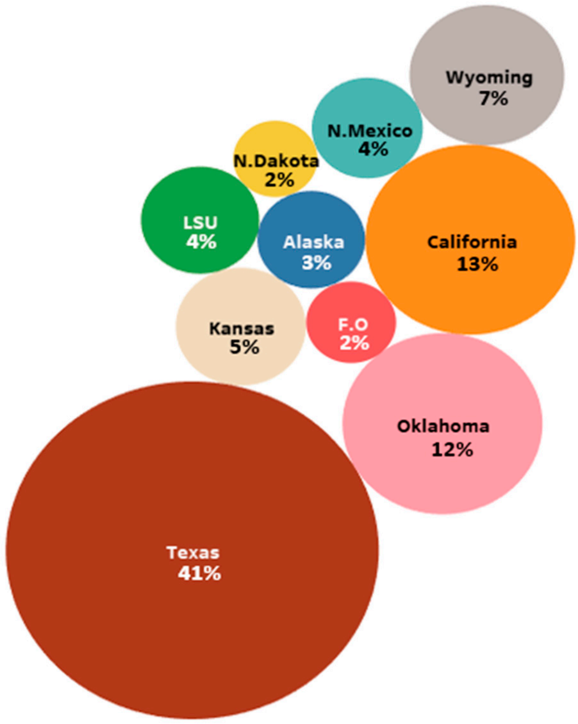

Figure 7. Top ten states in the US regarding produced water production (data from [42]).

Oil and gas production generates significant wastewater, necessitating effective management without harming the economy or environment. Effective treatment requires a comprehensive understanding of the effluent's features and properties and the consequences to the ecosystem in each country, as highlighted by [50].

Unconventional gas and tight oil reservoirs have low permeability compared to conventional oil and gas reservoirs (1–1000 mD). Hydrocarbon recovery is more challenging in these formations [51]. Hydraulic fracturing operations use hydraulic fracturing fluid, composed of water and proppant, with chemical additives accounting for less than 20% of the total volume. These additives can include friction-reducing polymers, liner gels, biocides, surfactants, and corrosion inhibitors. The use of hydraulic fracturing fluid is crucial for efficient oil and gas production [52–57].

Hydraulic fracturing, a process used in oil and gas production, consumes a significant amount of water, which is problematic in semi-arid basins where water availability is often stressed to meet demand. From 2000 to 2011, total freshwater consumption for shale gas HF activities in Texas ranged from 6.5×10^6 m^3 to 18×10^6 m^3 and up to 145×10^6 m^3 [58]. Between 2005 and 2014, the total hydraulic fracturing water volume for ten of the biggest US formations was around 940×10^6 m^3 [59,60]. Nearly half of the hydraulically fractured wells in the United States were in areas of severe or extreme water stress, with 97% of wells in Colorado falling into this category [61,62]. The median yearly water use for horizontal wells increased from 700 m^3 per well to more than 15,200 and 19,400 m^3 per well.

Figure 8 represents the average water use (m^3) for hydraulic fracturing of horizontal wells in major shale plays in the US. Huge volumes of water are needed for hydraulic fracturing of horizontal wells. For example, Eagle Ford (18,300 m^3), Barnett (18,900 m^3), DJ Basin (12,800 m^3), Bakken (8400 m^3), Marcellus (16,700 m^3), and Monterey (530 m^3) require high volumes of water [63]. The annual average water usages for the Permian and Williston basins regarding hydraulic fracturing operations account for 24,548 m^3 and 21,366 m^3, respectively [64].

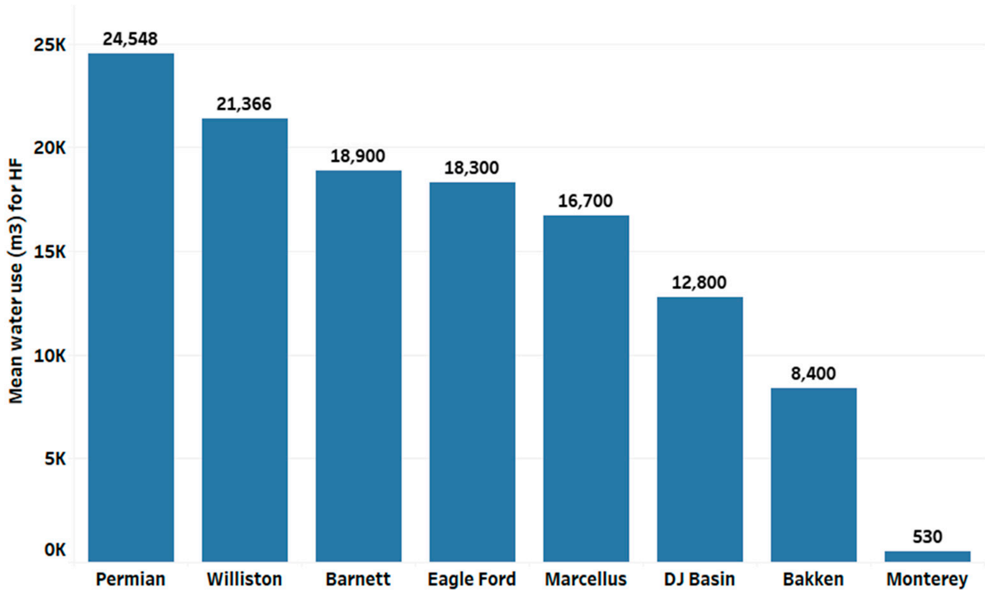

Figure 8. Average water use (m^3) for HF (hydraulic fracturing) of horizontal wells in major shale plays in USA (data from [63,64]).

3. Issues of Produced Water for the New Sustainability Challenge

Semi-arid western United States is home to the world's largest unconventional oil reserves [65–67], but water scarcity has increased due to increasing amounts of water used for HF, which is highest in the Permian Basin oil play [2,68,69]. HF has been related to another environmental problem, induced seismicity, in some areas [70,71]. Unconventional oil and gas reservoirs produce large quantities of water in addition to oil and natural gas, with the Permian oil play producing the most PW [68,72,73]. Most PW in the oil and gas industry is managed by injecting or disposing of it deep below [74,75]. Because these injections alter subsurface fluid budgets and pressures, they may cause induced seismicity. For example, in Oklahoma, most of the recorded earthquakes may be traced back to disposal close to the basement and heavily loaded faults [76–78]. Spills and leaks of fluids could contaminate water systems, and methane could seep into the groundwater [79–83]. Therefore, it is evident that PW management has become a challenging issue in the oil and gas industry, necessitating a long-term and cost-effective technology solution. Companies have been building their water midstream industry to address water management issues and have attracted considerable private equity investment.

4. Characteristics of Oilfield Produced Water

Produced water contains dissolved oily compounds such as BTEX, phenols, and hydrocarbons. Because of their solubility in water, a reservoir's pH, temperature, and pressure all have a role in determining how much of each chemical is there. Some alkylated phenols became less soluble in generated water, and PAHs were found to be coated in oily substances [84]. Produced water contains a wide variety of contaminants, including dissolved salts (Cl^-, Na^+, Ca^{2+}, $SO_4{}^{2-}$, $CO_3{}^{2-}$), radioactive elements (226 Ra, 228 Ra), and heavy metals and metalloids (As, Cd, Cr, Zn, Cu, Pb). Production solids include, but are not limited to, forming solids, particulate matter, microbes, asphaltenes, and corrosion products [85–88]. Increases in ionic strength and water temperature reduce the solubility of dissolved gases including volatile hydrocarbons, carbon dioxide (CO_2), oxygen (O_2), and hydrogen sulfide (H_2S) in petroleum brine [87]. However, the chemical compositions of petroleum production include corrosion inhibitors, biocides, anticoagulants, and dispersants [89].

4.1. Physicochemical Characteristics

The ranges of major physicochemical parameters in different primary shale plays in the US are represented in Figure 9. It shows the ranges of major physicochemical parameters of PW including pH, dissolved organic carbon (DOC), chemical oxygen demand (COD), total organic carbon (TOC), total dissolved solid (TDS), EC ranges, and turbidity.

The pH range of various shale types is varying, with Marcellus having a maximum of 7.9 and a minimum of 3.9, Woodford having a maximum of 9.3, Eagle Ford having a maximum of 8.9 and a minimum of 4.3, Bakken having a maximum of 2.5, Barnett having a maximum of 1.5, Sichuan Basin having a maximum of 8.2, and DJ Basin having a maximum of 7.42 [90–98].

The ranges of Total organic carbon (TOC) for various shale types are also varying. For the Marcellus shale play, TOC ranges are 5803 Δmg/L, Bakken's ranges are 2719 Δmg/L, Sichuan Basin's ranges are 1897 Δmg/L, DJ Basin's ranges are 663 Δmg/L, Woodford's ranges are 170 Δmg/L, Permian's ranges are 98 Δmg/L, and Barnett's ranges are 93 Δmg/L [94,95,98–105].

In terms of DOC, the maximum range is 5957 Δmg/L, DJ Basin's ranges are 2123 Δmg/L, Eagle Ford's ranges are 851 Δmg/L, Barnett's ranges are 86 Δmg/L, and Permian's ranges are 82 Δmg/L [92,95,98,105–108].

In Bakken, COD ranges are 59,000 Δmg/L; for Marcellus, 50,981 Δmg/L; for Barnett, 9670 Δmg/L; for DJ Basin, 7507 Δmg/L; for Sichuan Basin, 3119 Δmg/L; and DJ Basin's ranges are 430,800 Δmg/L [92,95,96,98,109–112].

TDS ranges for DJ Basin, Eagle Ford, Marcellus, Bakken, Woodford, Sichuan Basin, Barnett, and DJ Basin are also varying [90,92–94,98,105,111–116]

The TSS ranges for Permian, Marcellus, Eagle Ford, DJ Basin, Woodford, Sichuan Basin, and Barnett vary from 14,970 Δmg/L to 762,938 Δmg/L [90,92,95,96,105,107,111,115,117–119].

The EC range in Marcellus is 167700 Δmg/L, while that of Barnett is 277 Δmg/L [56,92,95,101,112]. Turbidity in Marcellus is 2998 NTU, while Eagle Ford and DJ Basin levels vary from 1726 NTU to 418 NTU [90,92,95,98,101,112,120,121].

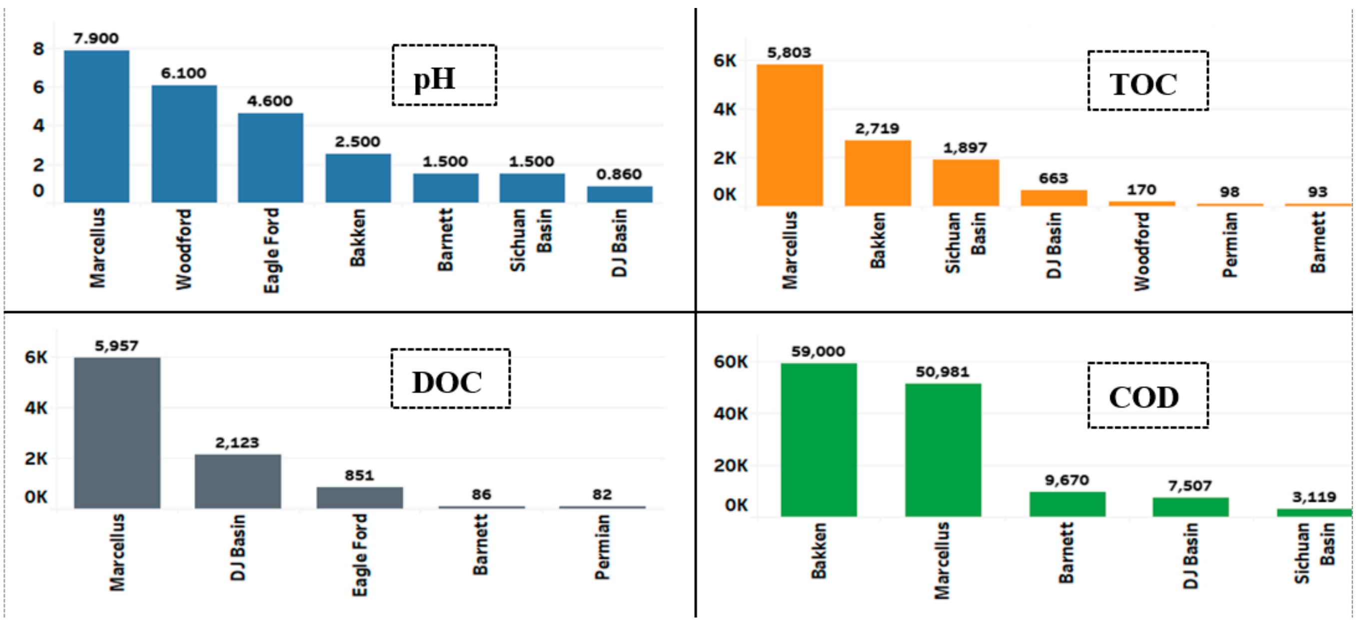

Figure 9. *Cont.*

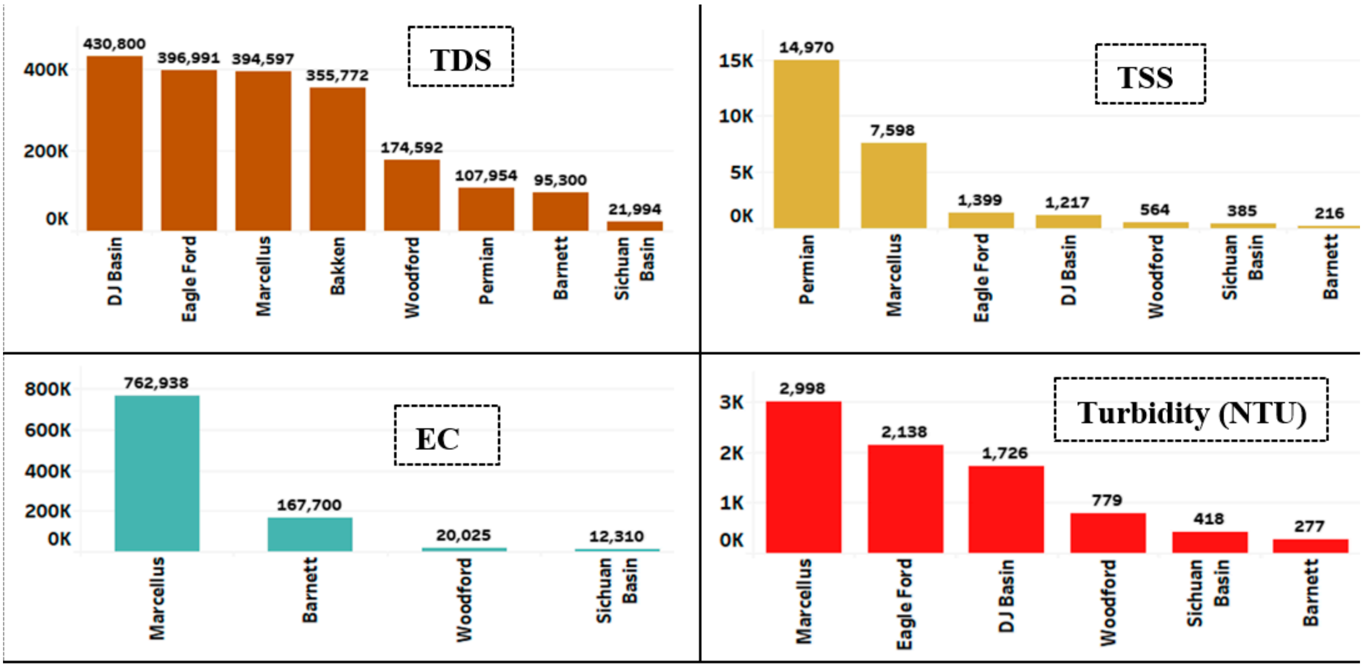

Figure 9. Ranges of concentration (Δmg/L) for major physicochemical parameters of PW in different primary oil and gas plays in the US (data from [92–128]).

4.2. Inorganic Characteristics

The inorganic characteristics of produced water are illustrated in Figure 10. The figure focuses on the concentration of various minerals in different types of soils, such as those located at Marcellus, Eagle Ford, Bakken, Woodford, Barnett, and DJ Basin. The concentrations of Ca^{2+}, Cl^{-}, Na^{+}, HCO^{3-}, Sr^{2+}, Mg $^{2+}$, Br^{-}, Ba^{2+}, and Ba^{2+} in the oil and gas plays Sichuan Basin and Permian Basin are analyzed.

The Ca^{2+} concentration in various basins ranks from highest to lowest as follows: Marcellus, Eagle Ford, Bakken, Woodford, Barnett, Permian, and DJ Basin [92,93,95,111,123,124]. The Cl^{-} concentration follows a similar pattern, with Eagle Ford having the highest concentration followed by Marcellus, Bakken, Barnett, Woodford, Permian, and DJ Basin [92–94,98,113,115,124].

The Na^{+} concentration is highest in Marcellus, followed by Eagle Ford, Bakken, Barnett, Woodford, DJ Basin, Sichuan Basin, and Permian [92,93,95,111–113,123–125].

The $HCO_3{}^{-}$ concentration in different oil and gas basins ranges from highest to lowest as follows: Eagle Ford, Sichuan Basin, Barnett, Bakken, DJ Basin, Marcellus, and Permian [93,101,106,115,123,124].

The Sr^{2+} concentration in different regions is ranked from highest to lowest as follows: Barnett (1502 Δmg/L), Bakken (977 Δmg/L), DJ Basin (186 Δmg/L), Woodford (116 Δmg/L), Sichuan Basin (92 Δmg/L), Permian (90 Δmg/L) [95,123].

Based on the provided data, the concentrations of Mg^{2+} in different shale formations are as follows: Eagle Ford (17,202 Δmg/L), Marcellus (13,000 Δmg/L), Bakken (1181 Δmg/L), Barnett (755 Δmg/L), Woodford (627 Δmg/L), Sichuan Basin (493 Δmg/L), and Permian (320 Δmg/L) [92,93,95,115,123–125].

In terms of K^{+} concentration, Marcellus has the highest value (5000 Δmg/L), followed by Woodford (2794 Δmg/L), Eagle Ford (1633 Δmg/L), Barnett (746 Δmg/L), Permian (530 Δmg/L), and Sichuan Basin (406 Δmg/L) [92,93,95,113,124,125].

Marcellus also has the highest Br^{-} concentration (3340 Δmg/L), followed by Barnett (764 Δmg/L), Bakken (564 Δmg/L), Permian (490 Δmg/L), Eagle Ford (260 Δmg/L), DJ Basin (202 Δmg/L), and Sichuan Basin (36 Δmg/L) [92,94,98,99,123,126,127].

Some of the basins with higher Ba^{2+} levels are Woodford (78 Δmg/L) [92]; Eagle Ford (49 Δmg/L) [121]; Bakken (25 Δmg/L) [94]; Barnett (17.8 Δmg/L) [95]; DJ Basin (17.2 Δmg/L) [118,127]; and Permian (16 Δmg/L). More Al^{3+} is found in the DJ Basin, 3.290 Δmg/L [80], than in the Sichuan Basin, 3.10 Δmg/L [101]; in Barnett, 2.096 Δmg/L [95]; and in Bakken, 0.90 Δmg/L [123].

Marcellus has a high concentration of Li^{2+} at 634 mg/L [92], Barnett has 37.4 mg/L [95], Bakken has 36.3 mg/L [94,123], and DJ Basin has 7.1 mg/L [127].

Higher $SO4^{2-}$ concentrations are found in Marcellus with 2920 mg/L [128]; Barnett, with 1140 mg/L [95]; Bakken, with 430 mg/L [94]; and DJ Basin, with 253 mg/L [98,127].

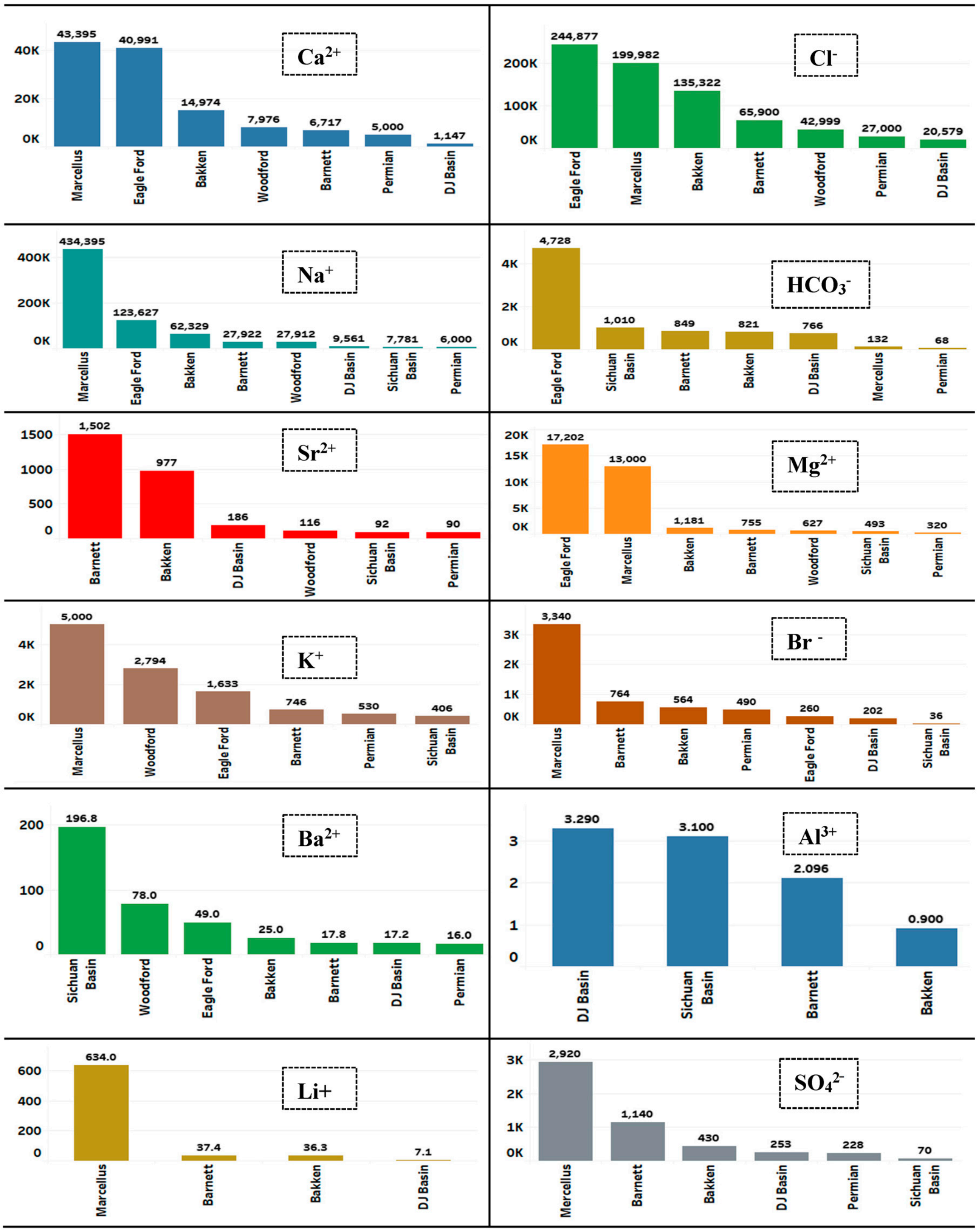

Figure 10. Ranges of concentration (Δmg/L) for major inorganic components in different primary shale plays in the US (data from [92–128]).

4.3. Organic Characteristics

Figure 11 depicts the ranges of major organic components in different primary shale plays in the US. The DJ Basin has the highest acetone ranges of 21.10 Δmg/L, followed by Marcellus with ranges of 7.49 Δmg/L and Barnett with ranges of 0.51 Δmg/L [30,92,95].

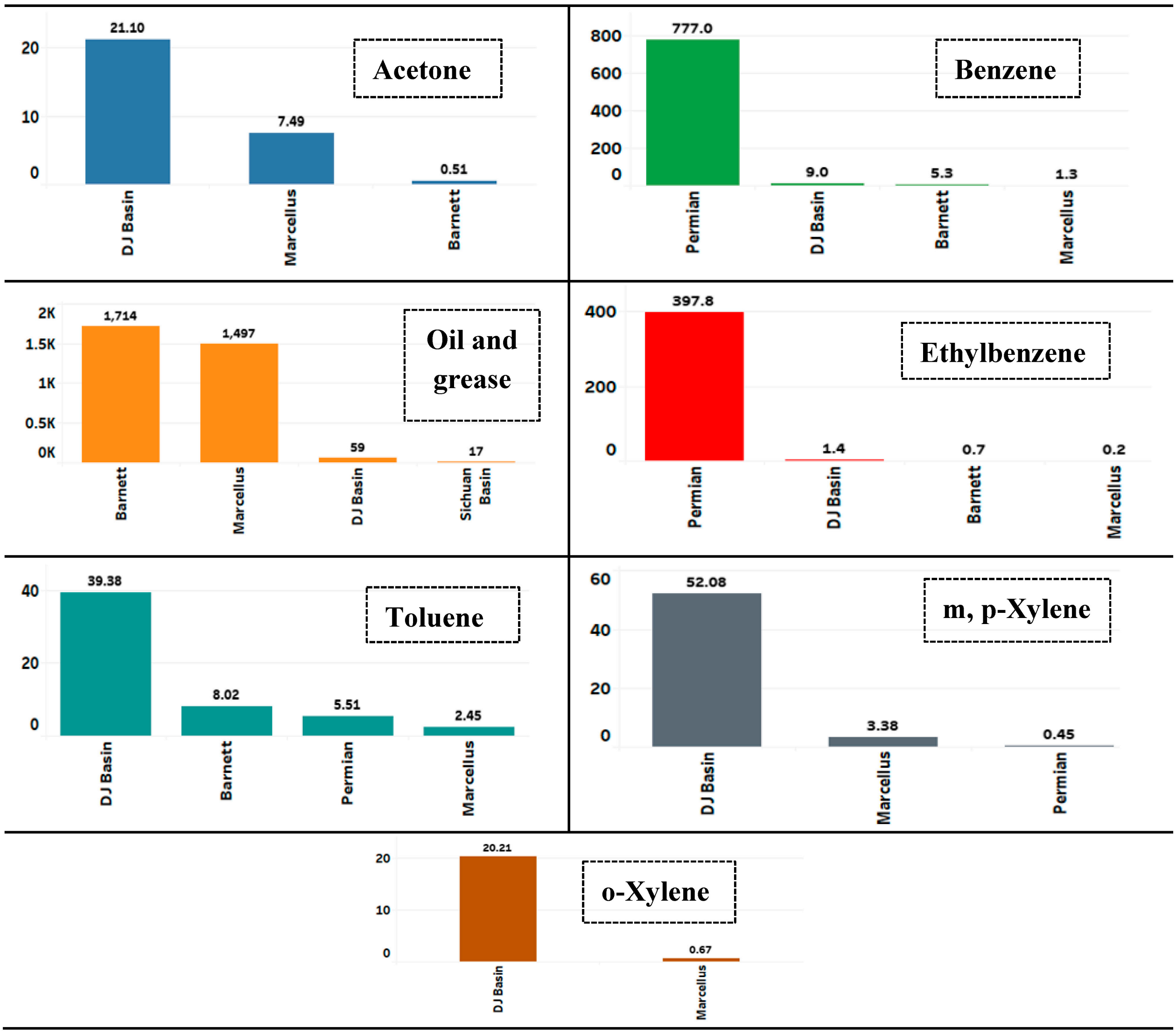

Figure 11. Ranges of concentration (Δmg/L) for major organic components in different shale plays in the US (data from [92–128]).

In terms of benzene concentration, the Permian Basin has the highest ranges of 777 Δmg/L, followed by the DJ Basin with ranges of 9 Δmg/L, Barnett with ranges of 5.3 Δmg/L, and Marcellus with ranges of 1.3 Δmg/L [95,105,113,129]. Oil and grease concentration is highest in the Barnett Basin with ranges of 1714 Δmg/L, followed by Marcellus with ranges of 1497 Δmg/L, the DJ Basin with ranges of 59 Δmg/L, and the Sichuan Basin with ranges of 17 Δmg/L [57,95,113,117].

The Permian Basin has the highest ethylbenzene ranges of 397.8 Δmg/L, followed by the DJ Basin with ranges of 1.4 Δmg/L, Barnett with ranges of 0.7 Δmg/L, and Marcellus with ranges of 0.2 Δmg/L [95,105,106,130]. The DJ Basin has the highest toluene concentration ranges of 39.38 Δmg/L, followed by Barnett with ranges of 8.2 Δmg/L, Permian with ranges of 5.51 Δmg/L, and Marcellus with ranges of 2.45 Δmg/L [92,95,105,129,130].

The DJ Basin has the highest m, p-Xylene concentration levels at 52.08 Δmg/L [129]; Marcellus has the lowest at 3.38 Δmg/L [130]; and Permian has the lowest at 0.45 Δmg/L [105]. The concentration of o-xylene in DJ Basin is 20.21 Δmg/L [129], and the concentration in Marcellus is 0.67 Δmg/L [130].

5. Produced Water Treatment Technologies

The environmental impact of oil and gas production is increasing due to the increasing demand for water. The proper treatment can help generate water, which can be a crucial source of freshwater in the face of scarcity [57]. Emphasis is on reclaiming, reusing, and recycling water to meet community scarcity. Treatment of petroleum by-products (PW) is an effective method for managing wastewater from offshore and onshore oilfields for irrigation purposes. PW treatment is non-toxic, useful, and can be applied to various industries, farm animals, wildlife watering, and power plant production [11]. Figure 12 represents the current practices of produced water treatment technologies available for the industry.

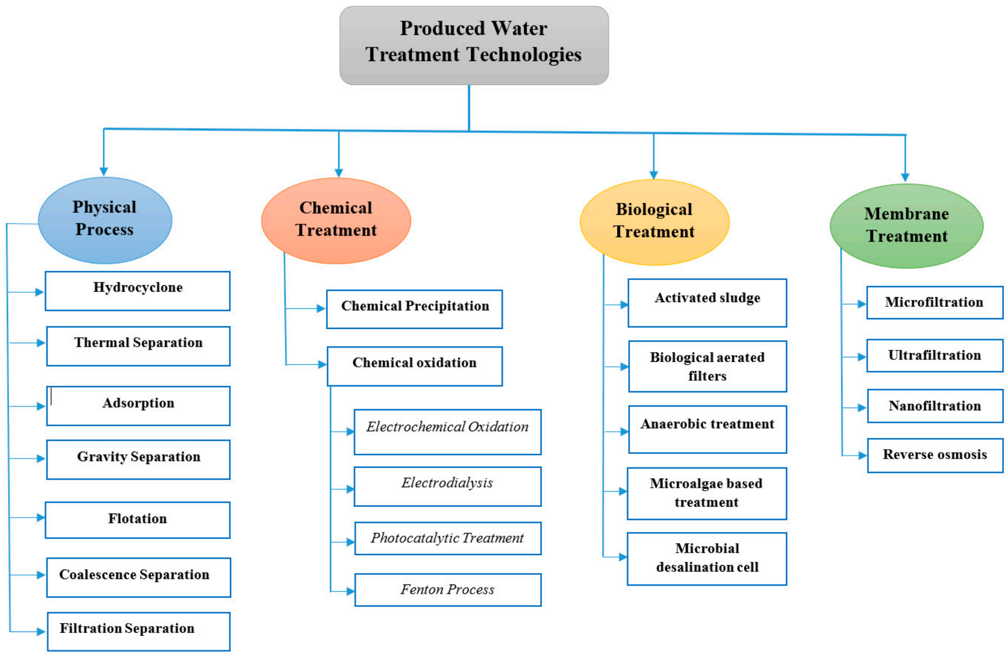

Figure 12. Flow chart for PW treatment technologies.

The primary aims for the treatment of PW could be explored [131–133] as follows:

(a) Elimination of fats and oils in free and dispersed states in PW;
(b) Removal of organic matter dissolved in PW;
(c) Elimination of different algae, bacteria, and microorganisms;
(d) Haze separation by removing colloids and suspended matter;
(e) Exclusion of gases dissolved in water;
(f) Elimination of minerals and dissolved salts, leftover water hardness, and possible probable radioactive substances.

5.1. Physical Process

5.1.1. Hydrocyclone

The hydrocyclone is a classical treatment method for produced water adopted to eradicate suspended solids, sand, and oil from PW [134]. The mechanism of elimination by hydrocyclone is mostly based on the differences in the density of different materials found in the PW to be separated [135]. The instrumentation of the hydrocyclone is simple. The essential part of the instrumentation is the cylindrical section on top, from which the

PW is inserted tangentially on a conical base. The angle of the conical section determines the separation capability and performance. The system has a bottom portion called the underflow or rejects stream for the denser fraction and an overflow or product portion for the less dense proportion of the liquid stream [136]. This system can remove particles to an extent of 5–15 μm, but it cannot remove soluble materials [137].

A large number of companies use the hydrocyclone for the treatment of PW. Due to space constraints, a small and compact system is required [137]. There are various advantages of using hydrocyclones such as not needing any chemicals or energy or any pre- or post-treatment stage. Sometimes, a forwarding pump is needed to deliver water to the hydrocyclone due to a plant-specific setup [138]. In the first step of its mechanism, it produces a stirring motion that creates a centrifugal force to act on the PW to separate the water with heavier material on the outside and the middle core of the cones is filled up with light oil. Then, the water flows downward and is separated from the tapered end [139].

5.1.2. Thermal Separation Process

Thermal separation techniques comprise a traditional process of PW treatment that was used for the desalting of PW [140]. Middle Eastern regions where energy resources are readily available and cost-effective use this process to treat the PW from oil and gas fields because this process requires high energy consumption [140]. There are two types of units in this process, namely multiple-effect flash units and multiple effect distillation units. In the MSF unit, the liquid from the oil and gas field is passed through multiple stages (more than 30), which act as countercurrent heat exchangers [141]. A heat exchanger and a condenser are connected simultaneously to each series of stages and help to maintain the hot and cold temperature at the end of each stage. The different temperatures and pressure help to separate salts from the PW in different stages according to the boiling point of these materials [14].

5.1.3. Adsorption

Adsorption is a method in which molecules are selectively moved to a solid surface from liquid owing to chemical bonds or van der Waals forces in the middle of the two phases [142]. This is a widely adopted treatment technology for the removal of hydrocarbons that are soluble in produced water. This can be attained by using a wide range of materials including organic clays, zeolites, chitosan, and activated carbon [143]. By using this process, it is possible to remove more than 80% of heavy metals and achieve an early 100% recovery rate of water from contaminated water [144]. The efficiency of this method is closely associated with the capability of the adsorbents to release impurities, which relies on temperature, pH, concentration, type, and the physical state of the adsorbents, along with the operating conditions applied [144].

It is well known from the literature that adsorbents are mainly picked and assessed based on their kinetics, characterization, and isotherms. Their characterization takes into consideration major factors such as pore size and volume, specific surface area, the kind of precursor used, cost, availability, and so on [145]. Additionally, it is of significant interest that a single absorbent is enough to maintain these factors to raise the execution of the process. Particles with large pores (between 2–50 nm) are mostly utilized as adsorbents because of their large surface area and the greater capacity of adsorbates to gather on these surfaces [146].

Investigations of isothermal batch and kinetic processes, although not used in industrial processes, are essential in laboratory experiments to evaluate the equilibrium time and to measure the total capacity of an adsorbent to absorb adsorbates from an aqueous phase under particular conditions owing to their simple configuration [147]. Adsorption kinetics explain the movement of adsorbates over time in an adsorbent. Factors such as pH, temperature, ionic initial adsorbate concentration, agitation, strength, and pore size and particle size distributions are some limitations influencing the steps of the process [148]. Mathematical models are frequently formulated and adopted to comprehend and forecast adsorption kinetics and to detect the control mechanism. The empirical models frequently applied are pseudo-first-order, pseudo-second-order, Elovich, and intraparticle diffusion models [149]. Comparisons of different adsorption capacities of the above contaminants with different adsorbents are illustrated in the bar chart in Figure 13.

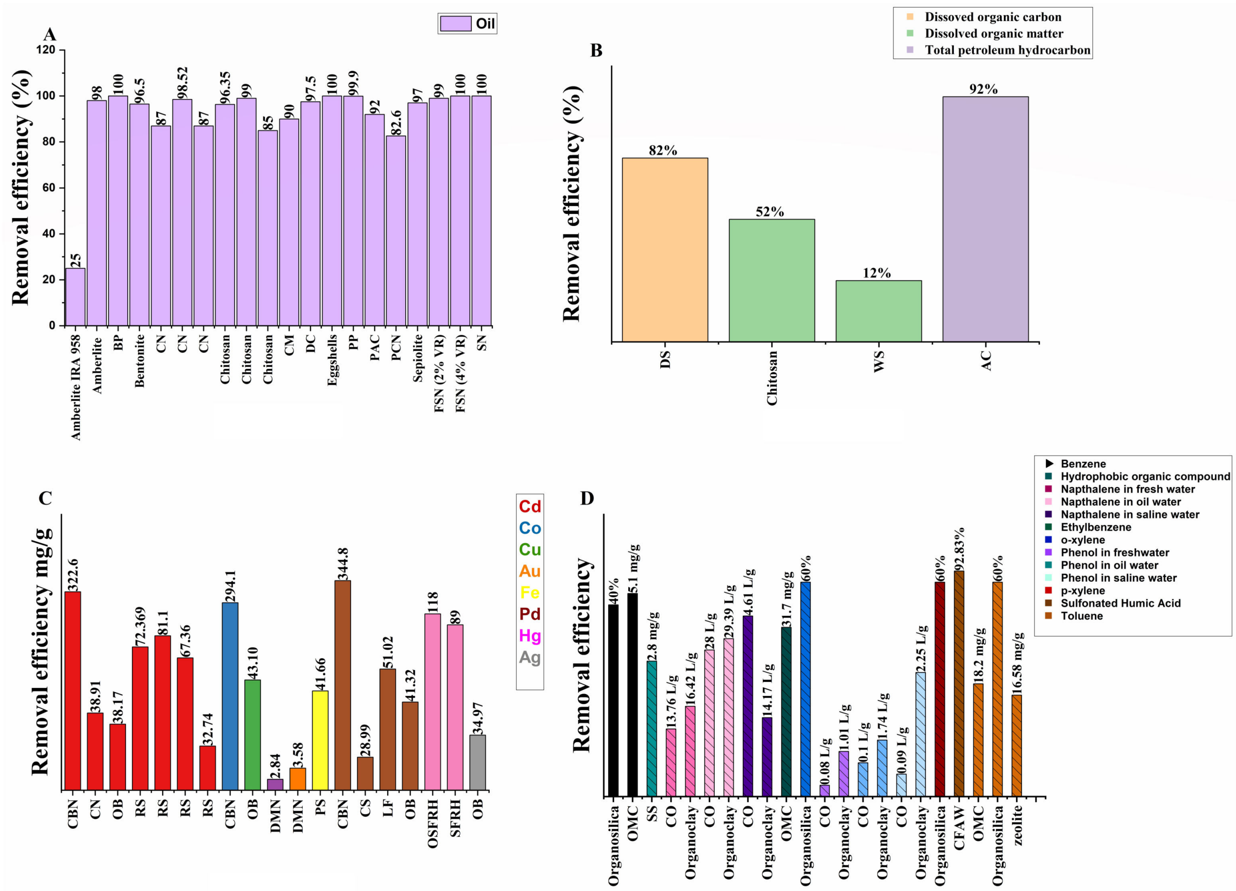

Figure 13. Comparison of removal efficiency for different contaminants—(**A**) oil, (**B**) dissolved organic matters, (**C**) metals (Cadmium-Cd, Cobalt-Co, Cupper-Cu, Gold-Au, Iron-Fe, Palladium-Pd, Mercury- Hg, Silver-Ag), and (**D**) chemical compounds in different adsorbents (BP- Banana Peel, CN-Carbon Nanotube, CM-Carbon Methyl, DC-Deposited Carbon, PP-Pineapple Peel, PAC Powder Activated Carbon, PCN-Poly Carbon Nanotube, FSN-Functional Silica Nano-particle, SN-Silica Nano-particle, DS-Date Seed, WS-Wheat Straw, AC- Activated Carbon, CBN-Camel-bone Nano-composite, CN-Carbon Nanotube, OB- Olive Brunches, RS-Rape Straw, DMN-Dendrimer Magnetic Particle, PS-Pomegranate Seed, CS-Corn Straw, LF-Low-density Fly ash, OB-Organic bentonite, OSFRH-Organosilanes Functionalized Rice Husk, SFRH-Sulfur Functionalized Rice Husk, OMC-Ordered mesoporous Carbon, SS-Sewage Sludge, CO-Commercial Organo-clay, and CFAW-Coal Fly-ash waste (data from [142–149]).

Although this technique is widely extensively utilized and may represent empirical trends, caution should be implemented when utilizing this approach. This is because the kinetic models require many operational supplies and physical processes and cannot be employed to explain a system beyond the conditions deemed for its fitting [150]. At this point, mechanistic and phenomenological models are well matched. They are based on equilibria, transport kinetics equations, and conservation and not on experimental attempts [151]. There are a large number of adsorbents used to remove oil, soluble heavy metals, organic carbon of various natures, and organic substances such as naphthalene, toluene, xylene, phenol, benzene, humic acid, etc.

5.1.4. Gravity Separation

The most frequently used water purification process depends on gravitational forces to pull out droplets of oil from the continuous aqueous phase [152]. A gravitational force on oil droplets that are lighter than water is responsible for the displacement. This is counteracted by a force of dragging which is triggered by the vertical movement of water [153]. The oil and grease elimination process depends on the end utilization of the water and the oil's composition in the produced water. The preliminary gravity separation apparatus consists of classical gravity oil–water separators and a corrugated plate separator (CPI) [154].

The oil–water separators are conventional baffle-type separators and can eradicate oil particles greater than 150 μm [155]; the CPI can remove oil droplets 40 nm in size and its treatment capacity is higher than that of the American Petroleum Institute (API) separator [156]. Furthermore, the skim tank is also a general apparatus for oil–water separation and depends on gravity. A suitable upgrade to the classical gravity separation system has also been developed [157]. Forero et al. [158] mounted an additional structure to the gun barrel separation tanks and attained better dehydration degrees. The composition of PW is comparatively complex, and PW treatment by gravity separation only cannot meet wastewater quality needs.

5.1.5. Flotation

Flotation is a method of water treatment that utilizes gas bubbles to split up small, suspended particles that are hard to remove owing to settling [159]. In this technique, fine gas bubbles are introduced for the elimination of suspended particles that are very hard to remove by the sedimentation process [160]. Gas is inserted into the contaminated water and attracts suspended oil droplets and particles in the water to the resultant air bubbles. This produces foam on the surface, which is generally removed by floating. Furthermore, dissolved gas flotation effectively removes volatile organic substances in addition to oil and grease [161]. Dissolved air flotation has been extensively utilized to deal with produced water contamination.

The method of gas flotation has two categories, namely induced gas flotation (IGF) and dissolved gas flotation (DGF) [158]. These two methods are different from each other in the technique applied to produce gas bubbles and the sizes of resulting bubbles. First, the gas (normally air) enters the chamber in the DGF method, which is loaded with a completely saturated solution [161]. Within the chamber, the gas is distributed by using a vacuum or by generating a fast pressure drop. However, IGF technology has automatic shear or propellers to formulate bubbles that enter the end of the chamber of flotation [162]. The ability of the technique entirely relies on the pollutants to be separated, density variations in the aqueous solution, temperature, and the oil droplets.

There are several benefits and drawbacks of the gas flotation techniques. The benefits include: (i) coalescence raises the processing capacity; (ii) operation is very easy; (iii) instrumentation has no moving apparatus; (iv) it is durable and robust [158]. The drawbacks are that the performance efficiency is restricted to the oil droplets which are bigger than 25 microns and the flotation process does not work out preferable feed streams with elevated temperatures [163]. However, the techniques work efficiently under lower temperatures and can be applied to treat produced water with high or low total oxygen content (TOC) concentrations and water containing particulates, oil, and grease with a 7% solids content [160]. Particles with a size of 25 are eliminated by the DGF process, and when the coagulation process is used as a pretreatment step, the 3–5 μm size pollutants can be removed [164].

5.1.6. Coalescence Separation

In the coalescence separation technique, the dispersed particles in PW are passed through a reactor set up with the materials for coalescing which are capable of eliminating the homogeneously dispersed and emulsified greases and oils [165]. The working methods of the applied coalescer in this process are illustrated as whenever oil droplets are close together in the PW, a film of particles is formed automatically between the droplets [166]. When the thickness of this film is adequately small, the electrostatic force of attraction breaks down the film and several small droplets of contaminants unify into the one bigger droplet. The function of a coalescer is often influenced by the velocity of fluid, droplet diameter, pressure, interfacial curvature interfacial tension, etc. [167]. Coalescers usually used in the industry are particle bed coalescers and fiber bed coalescers and represent high productivity, accessible installation, simple operation, and bed cleaning. Compared with the gravity separation process, the coalescence separation technique has a more efficient structure, more separation precision, and an extended service life of materials [168]. In some instances, however, the layer of coalescing particles can be closed by solid particles and sludge.

5.1.7. Filtration Separation

Filtration is a straightforward technique utilized in water and wastewater treatment processes and is based on the application of porous filter media which particularly permit water to pass through but not pollutants [169]. Numerous porous materials such as gravel, sand, and activated carbon can be adopted as filter media. However, the most extensively applied material is sand owing to its abundance in the environment, low price, and efficiency [170]. A detailed summary of the pros and cons of all physical processes are illustrated in Table 1.

Table 1. Summary of physical treatment processes for oilfield PW.

Method	Target of Removal	Pros	Cons	Results	References
Hydrocyclone	5–15 µm suspended Solid, Dispersed, and free oil in PW	(1) Does not require moving different parts (2) Pretreatment process is not required	(1) Cleaning and proper maintenance are required (2) Solids may clog the inlet system	(1) More than 90% separation rate (2) 60 mg/L oil concentration in the contaminated water can be removed (3) Hydraulic resistance time is short	[8,134,135]
Thermal Separation process	different stages according to the boiling point of these materials.	Readily available and cost-effective for the Middle Eastern region	High instrumentation is required, and it is hard to control the process	More than 90 percent of organic substances can be removed	[10,141,171]
Adsorption	Most of the pollutants in PW	Treatment efficiency is good; water recovery is approximately 100%	Phase-transferred contaminants require secondary treatment	Lowering initial oil concentration, volumetric flow rate, particle size, and bed height increases oil removal rate	[143–148]
Gravity Separation	Large SS; Free and dispersed oil.	(1) Low-cost, easy operation (2) High processing power (3) Stable treatment efficacy (4) Chemical-free	(1) Big footprint and expensive startup (2) Retention duration increases with smaller oil droplets	(1) >99% dehydration (2) Treatment capacity increased >350%	[148,152–154]

Table 1. *Cont.*

Method	Target of Removal	Pros	Cons	Results	References
Flotation	Dispersed and emulsified oil (0.25–25 μm)	(1) Mature change (2) Good effectiveness of treatment	It cannot treat greasy wastewater with various oils	(1) <50 mg/L oil concentration (2) Bicyclone and dissolved air flotation devices produce effluent with oil droplet sizes of 3.97 μm and 7.21 μm, respectively	[154–161,163,164,172–174]
Coalescence separation	Emulsified oil	(1) Compact build (2) Very accurate separation (3) Long-lasting coalescing materials	Solid particles and sludge might clog coalescence layer	After 180 s and 30 psi pressure reduction, oil pollutant concentration dropped from 1200 to 25 mg/dL	[165,167]
Filtration separation	Large SS; Oil	(1) Low-cost, easy operation (2) Effective therapy (3) Backwash-friendly (4) Salinity is ineffective	Filter medium can be blocked, and backwashing is needed	(1) Over 85% of oil and suspended particles are removed (2) Greater than 98.8% filter material generation	[162,169]

5.2. Chemical Treatment

5.2.1. Chemical Precipitation

In the context of chemically treating produced water, precipitation is considered a standard approach. Over 97% removal of suspended and colloidal particles is possible using this method [169]. It is possible to use coagulation and flocculation to filter out suspended and colloidal particles; however, they cannot be used to filter out dissolved elements. Inorganic metals including iron, magnesium, and aluminum polymers form the backbone of these techniques, and they have been shown to be effective in eliminating pollutants during the chemical treatment process [175,176]. Particles, carbonaceous chemicals, phosphorous, and metals were removed in another study using a flocculation unit and polymer anions such as ferric chloride ($FeCl_3$). But it was found that these flocculants were not very good at keeping out nitrogen molecules and hydrophilic chemicals [177]. It has also been stated that almost 97% of oil and suspended solids may be eradicated from produced water by including the chemicals for coagulation [178].

Produced water containing 200 ppm of oil, 500 ppm of sulfides, 2000 ppm of hardness, and 10,000 ppm of TDS can be efficiently converted into steam generator-quality feedwater by modified hot lime procedures [8]. When compared to the traditional hot lime method, this approach has the potential to significantly cut down on both alkali consumption and sludge production. In produced water with greater SS levels, this chemical exhibited well coagulation, scale inhibition, and de-oiling [179]. Houcine also used spills or calcite and lime in an experiment to remove heavy metals from produced water. Lime's cost-effectiveness and greater elimination efficiency (>95%) were demonstrated by the results [8]. Researchers used oxidants, ferric ions, and flocculants to remove arsenic, hydrocarbons, and mercury from treated water [138].

5.2.2. Chemical Oxidation

Chemical oxidation is a common method for treating compounds in contaminated water, using catalysts, a strong oxidant, and irradiation (not including ozone treatment). This method lowers COD, BOD, odor, color, certain organics, and inorganics in PW [4].

According to Igunnu and Chen [180], free electrons cannot be in the solution; hence, this treatment technique relies on groundwater redox reactions.

Huang [181] suggests breaking up organic contaminants in PW with catalysts and powerful oxidizers. Oxygen, ozone, peroxide, and chlorine can degrade many pollutants. The chemical dose, oxidant type, raw water quality, and oxidant–water contact time affect this method's oxidation rate [178]. This treatment process uses minimal equipment, produces no pollutants, requires no pretreatment, and recovers about 100% of PW. However, the technique's byproducts are difficult to separate, chemicals are expensive, and pump maintenance and calibration are required [4].

To remove all contaminants, Igunnu and Chen [180] recommended a final treatment. Advanced oxidation processes (AOP) are a recent breakthrough in water treatment and use oxidants or a mixture of oxidants to quickly oxidize organic pollutants [182]. AOP techniques create potent oxidizing radicals, mostly hydroxyl. The produced hydroxyl radicals react swiftly and non-selectively with practically all organic compounds containing more electrons [4]. Hydroxyl groups can transform high-molecular-weight organic compounds into minerals [181]. Non-conventional AOP include humid oxidation with peroxide and moist air oxidation. Chemical oxidants include hydrogen peroxide, iron, and ozone. This treatment generates hydroxyl radicals using titanium dioxide, iron oxide, and zinc oxide [183].

Electrochemical Oxidation Process

Research into electrochemistry, which focuses on improving chemical reactions involved in the production or use of electricity, represents a low-cost green approach in comparison to other current treatments for PW. It improves the beneficial utilization of PW without creating secondary waste or necessitating the use of additional chemicals [86]. Incorporating an electrochemical process with some of the aforementioned chemical techniques to produce clean water, store energy, and recover precious metals from oilfield PW is a promising alternative for PW treatment [178].

Electrodialysis (ED)

Ionic PW salts can be eliminated by oppositely charged electrodes. ED allows either anions or cations to pass through membranes placed between two oppositely charged electrodes (Patel et al., 2020). Each set of membranes has a spacer sheet to allow feed water to travel down the membrane face. Ions with positive charges (e.g., Na^+) go to the cathode, whereas those with negative charges (e.g., Cl^-) go to the anode [184]. The same-charge ions in ion-exchange membranes exclude ions with specific charges during migration. Thus, alternating cells concentrate ions while diluting nearby ions [185]. Through cell frame inlets and outlets, membrane cells can pass diluted and concentrated solutions. ED successfully treated PW from a conventional well in Wyoming's Wind River Basin with oil, organic acids, BTEX, H_2S, dissolved solids, and more [186]. Fernandez et al. [187] investigated polymer-flooding produced water (PFPW) desalination by an electric field pulsed through ED. This study desalinated synthetic PFPW under various operating circumstances until a specified number of charges were gone. PEF enhanced the ED's performance, demineralization, and energy usage by 36% compared to the continuous mode.

Photocatalytic Treatment

Photocatalysis wastewater treatment is a promising AOP for pollution remediation [188]. This approach removes many organic pollutants without chemical oxidants at ambient temperatures and pressures [189,190]. This method removes most soluble oils from PW. This disruptive process uses little to or no chemicals and produces no waste sludge [191].

Organic pollutants in PW initially react with oxygen in the presence of photo-catalysts. Photocatalyst semiconductor materials produce CO_2, H_2O, and mineral acids. Photocatalyst performance depends on catalytic dosage, light wavelength and intensity, pH, salts and pollutants, and temperature [192]. Photocatalytic oxidation of PW is understudied compared to other treatments, and its suitability and methodologies for treatment success are unknown. PW ions including phosphate, carbonate, bicarbonate, nitrate, nitrite, and chloride affect photoelectron generation, electron–hole recombination, and hydroxyl radical scavenging. Ionic strength from chloride, calcium, magnesium, and sulfate can vary adsorption concentration and type. However, excessive organic matter in PW blocks adsorption sites, hydroxyl elimination, and light adsorption, making it a major inhibitor of PW treatment.

Classical physical separation methods must remove suspended oil, grease, and particles from PW to improve photocatalytic efficiency. Thus, this technique can be used as a pretreatment before biological treatments to reduce TOC, break big organic compounds, improve biodegradability, and minimize PW toxicity. After-treatment photocatalysis can remove leftover contaminants to improve produced water quality. Photocatalysts with improved specific surface area and self-cleaning ability must also be studied [193]. A detailed summary of chemical treatment processes for oilfield PW is provided in Table 2.

5.3. Thermal Treatment

Thermal technology extends systems' lifespans and treats highly contaminated water. It is employed in instream water streams with high salinity concentrations, like those in Gulf Cooperation Council (GCC) countries, where the recommended limit is 32 mg/L [194]. This technique has a somewhat low recovery rate, hovering around 20% [188]. Multiple processes, such as multistage flash (MSF), multieffect distillation (MED), and vapor compression distillation (VCD), are used in thermal treatment. All of these techniques for cleaning PW rely on the water's natural ability to evaporate and condense to remove impurities. Following are the most common thermal treatment methods [190,194].

Table 2. Summary of chemical treatment processes for oilfield PW.

Methods	Target of Removal	Pros	Cons	Results	References
Chemical precipitation	Suspended and colloidal particles, hardness, heavy metals	(1) High recovery, simple operation, low cost, and energy-saving. (2) The pretreatment step is unnecessary	Secondary trash, sludge, chemical needs, metal-rich effluent	Excellent in cost saving	[8,189,195]
Chemical oxidation	Heavy metals, TDS, organics, BTEX, bacteria	Chemical-free, helpful secondary products, eco-friendly	(1) Scaling issues, expert labor needed (2) Process monitoring, optimization, pretreatment, and specialized labor are necessary for low-pollution wastewater	Environmentally friendly	[14,180,196]

5.4. Biological Treatment

Biological treatment methods reduce COD efficiently [197–200]. They are eco-friendly because they do not pollute. They utilize chemical substances, but not the physical disinfection. However, biological treatment cannot eliminate TDS [201,202].

Figure 9 summarizes biological PW treatments. In ex situ bioremediation, manmade wetlands or bioreactors improve biodegradation. Aerobic and anaerobic processes can bioremediate in situ. Bioaugmentation or bio-stimulation may be needed to speed up or stop pollutant biodegradation. Bio-stimulation adds trace minerals, soil nutrients, and electron donors or acceptors to speed up PW pollutant biodegradation, whereas bioaugmentation adds an exogenous mixed culture. This section discusses PW biological therapy advances.

5.5. Membrane Treatment

Membrane filtering technology is popular worldwide because it may be employed in numerous industries, including the oil and gas industry [203–205]. Membrane technology can overcome the limitations of current treatment methods, such as expensive setup, hazardous chemicals, instrument design, and undesired byproducts [131]. Membrane treatment technology can be incorporated into interface engineering methods like biomimetic coating, atomic layer deposition, and surface functionalization with advanced nanomaterials. These methods provide high antifouling ability and improve water treatment efficiency in challenging oil/water mixtures and emulsion separations. These efforts enhance water treatment efficiency and address oil/water mixtures and emulsion separations [133,206–210].

5.6. Hybrid Technologies

To remove pollutants and reduce environmental damage, oilfield wastewater is treated using various types of technologies (physical, chemical, thermal, biological). Membrane treatments and other methods remove or minimize pollutants. However, single treatment methods have not addressed all recycling and landfill needs. The following combinations of methods have been proven to effectively remove a wide range of wastewater pollutants.

A detailed summary of thermal, biological, and membrane treatment processes for oilfield PW is provided in Table 3.

Table 3. Summary of thermal, biological, and membrane treatment processes for oilfield PW.

Methods	Target of Removal	Pros	Cons	Results	References
Thermal	Salts	Long-lasting, mature, sturdy, easy to use, suited for high-TDS samples.	Reduced recovery rate, corrosion and scale inhibitors needed, energy usage.	Simple in use	[211,212]
Biological	BTEX, TDS, SS, organics	Low-maintenance, cost-effective, high-water recovery	High retention time, requires sludge disposal	Cost-effective	[137,213]
Membrane Distillation	TDS, dissolved organics, salts, hydrocarbons	Compact, automated, high pH tolerance, removes dissolved impurities and monovalent salts, energy-efficient, chemical-free, greater capital cost than microfiltration and nanofiltration.	Membrane fouling, additional waste formation, high pressure, and demand for more energy than nanofiltration	Excellent in automation	[178,180,211, 214–219]

6. Sustainable PW Management

Sustainable oilfield water management is essential for responsible oil and gas exploitation, environmental protection, and water conservation. Every day, millions of barrels of PW are produced all over the world. Apart from providing a risk of water resource contamination, these effluents are directly linked to corrosion and scale in refinery pipelines [8]. The sort of treatment and disposal strategy chosen is determined by the technical feasibility, price, and availability of technology and facilities, as well as current legislation [220]. A typical produced water management workflow is shown in Figure 14.

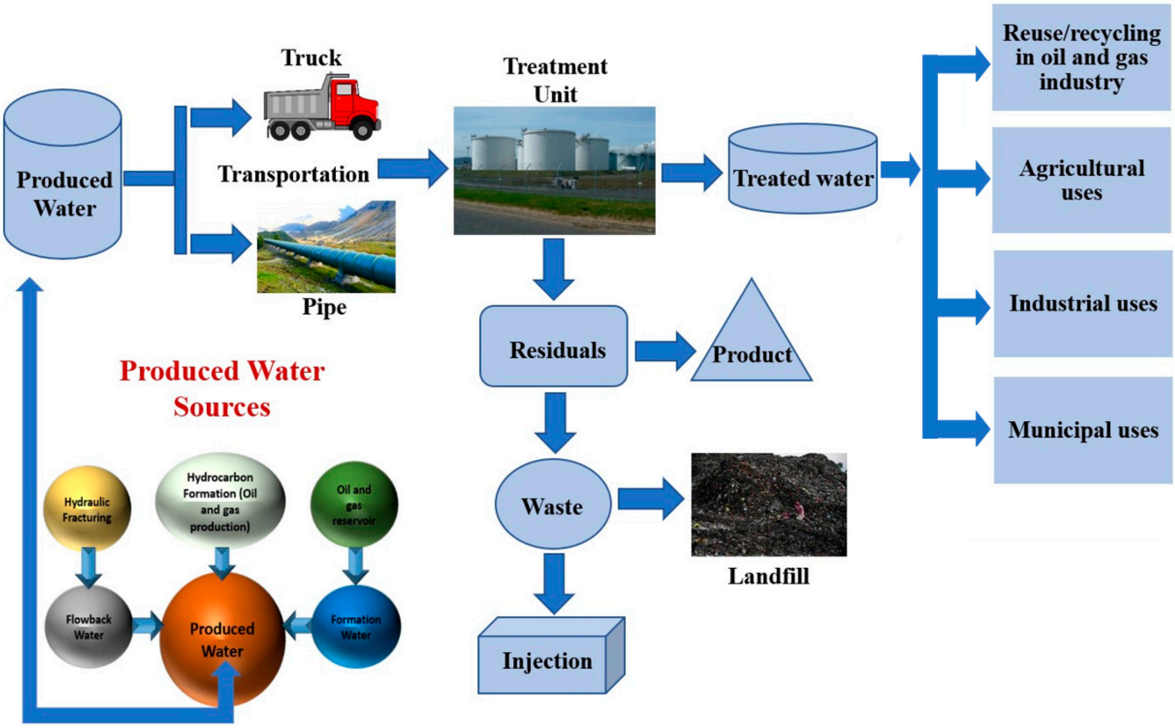

Figure 14. Typical produced water management strategies.

6.1. Treatment Aspects

Primary, secondary, and tertiary treatments can address PW effluent and management limits [221]. The primary operation usually removes free O&G, solids, and particles. Secondary treatment removes oil droplets and particulates. Tertiary treatment removes residual contaminants, improving water quality estimates for disposal or reuse [8]. Technology that reduces PW production, reuse and recycling of effluent, and, if required, disposal in the environment are the main methods for controlling PW onshore and offshore. Recovery, reuse, and recycling can control PW when process reduction fails. Injection, industrial, irrigation, and beneficial usage are choices [178].

Adsorption, membrane filtration, advanced oxidative processes (AOP), and biodegradation have been studied for PW treatment [43]. Physical and chemical therapy can address many instances of PW. Flotation, filtration, electrodialysis, cyclones, sand filters, evaporation, DAP, and adsorption are physical treatments. Chemical treatment methods use precipitation, chemical oxidation, photocatalysis, the Fenton reaction, demulsifiers, ozone, and electrochemical technologies. Active sludge, biological aerated filters (BAF), novel micro-capacitive desalination cell (MCDC), and microalgae-based treatments are biological treatments. Microfiltration, ultrafiltration, nanofiltration, and reverse osmosis membranes are examples of membrane technology [8,131,222].

Future technologies include electrochemical water purification. They are low-cost, environmentally benign, and do not require chemicals or generate secondary waste, making them better than other treatment systems. They also remove organic pollutants, generate and store energy, and recover vital elements from produced water without damaging the environment [180]. PW treatment efficiency and convenience depend on chemical agents. Bactericides, descalers, and corrosion inhibitors stabilize systems.

Water purification agents, which demulsify, flocculate, and modify water quality, are the most significant chemicals for effective PW treatment. Offshore PW purification can use quaternary ammonium, carboxylate, sulfonate, or poly-phosphate ester demulsifiers. Stabilization corrosion inhibitors used in offshore PW treatment include borate, organic amine, mercaptan, sulfonate, polyphosphate, molybdate, and tungstate [135].

6.2. Regulatory Aspects

To make sure that oil and gas businesses follow ethical environmental standards, regulatory requirements are essential for sustainable management of produced water from oilfields. Federal, state, and municipal governments, as well as other organizations, often establish these policies. Regulatory responsibilities [223] may consist of the following:

- Comply with the reporting obligations specified by the appropriate environmental agencies and obtain permits prior to discharging, injecting, or storing produced water. These include NPDES (National Pollutant Discharge Elimination System) and state-issued licenses, as well as UIC (Underground Injection Control) well permits;
- Conform with the criteria and standards for water quality that have been established by state and federal regulatory agencies. These standards establish the maximum allowable concentrations of various pollutants in the produced water and the bodies of water it may contaminate;
- Comply with standards governing the disposal and transportation of hazardous and non-hazardous waste generated during the treatment and handling of produced water. This may include following the Resource Conservation and Recovery Act (RCRA) regulations;
- Create and implement spill prevention and response plans to avoid inadvertent leaks of produced water or other contaminants. It is crucial to adhere to the regulations outlined in the Clean Water Act (CWA) and the Oil Pollution Act (OPA);
- Consistently monitor and provide regulatory authorities with reports on the quantity and quality of produced water, emissions, and discharges; frequently use electronic reporting systems. It is imperative to acquire the appropriate permits for UIC wells and adhere to the prescribed guidelines for injection wells, which may encompass pressure monitoring, mechanical integrity testing, and wellbore integrity assessments;
- In order to mitigate soil erosion and sediment discharge into water bodies, it is imperative to enforce erosion and sediment control measures mandated by regulatory agencies throughout the construction and operation phases. It is imperative to adhere to regulations pertaining to environmentally friendly completions and emission control, such as the Clean Air Act (CAA) and the implementation of best available control technology (BACT), to mitigate emissions;
- Ensure adherence to regulations pertaining to concentrated brine disposal and Zero Liquid Discharge (ZLD) systems, which may encompass standards for permits and disposal;
- Ensure that activities that have the potential to affect the environment or public health are duly communicated to the public and involve local stakeholders and communities in a manner consistent with regulatory requirements;
- Adhere to the stipulations placed forth by specific regulatory authorities with regard to the financing of research and development initiatives that seek to enhance technologies for water treatment and management;
- As required by federal and state agencies, conduct environmental impact assessments to determine the potential environmental effects of oilfield activities, such as produced water management;
- In order to verify compliance with relevant environmental regulations, regulatory authorities should conduct routine inspections and compliance assessments of the oilfield;
- Comply with standards governing the closure and remediation of oilfields, including produced water management facilities, to avoid long-term environmental damage.

Depending on where they operate, oil and gas businesses may be governed by different laws and authorities in different areas. Companies must maintain a sustainable and environmentally responsible approach to produced water management in oilfields by collaborating closely with regulatory bodies and ensuring stringent adherence to all applicable obligations. Noncompliance can result in fines, legal action, and damage to a company's reputation. Typical regulatory aspects are summarized in Figure 15.

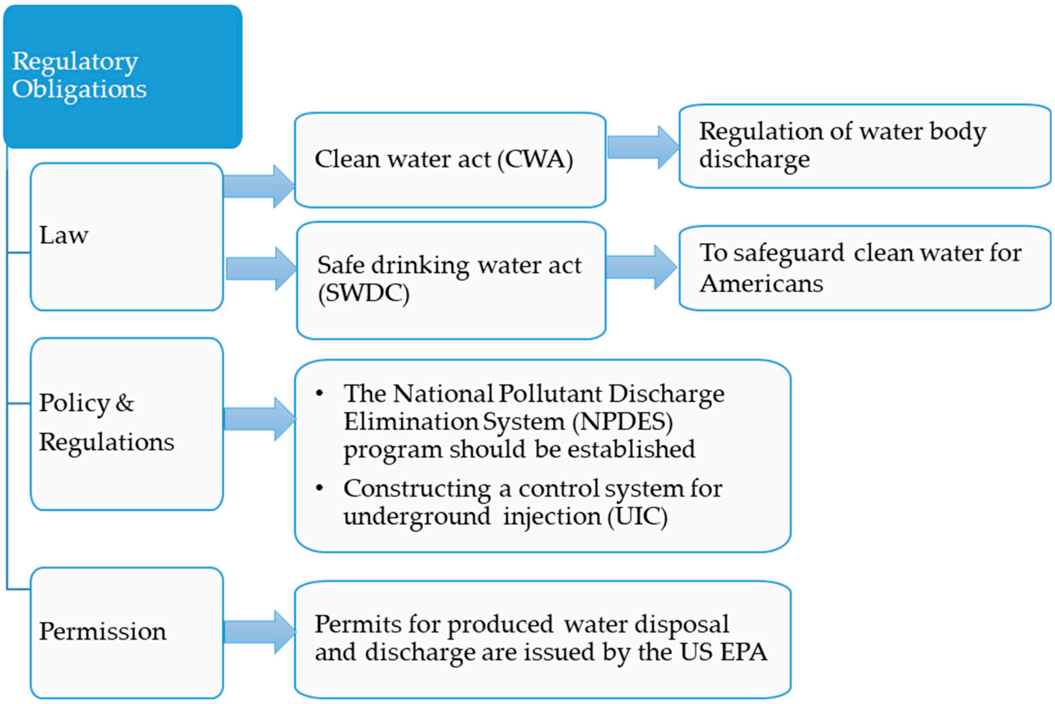

Figure 15. Regulatory obligations for PW management.

7. Future Outlook of PW Treatment Technology

Despite the common misconception that produced water is toxic waste, proper handling can be beneficial. As the world's population grows, demand for treated water increases. Current technologies lack energy efficiency, and future implementation is hindered by costs associated with pretreatment, contamination, and backwashing. Innovative approaches to lessen environmental effect, increase efficiency, and maximize water resource reuse are anticipated to define the future of oilfield produced water treatment technology and management. Various innovative methods and technologies have been developed for treating water from oilfields, attracting significant interest in the field. The adoption of these techniques varies based on oilfield conditions, regulatory requirements, water characteristics, environmental factors, and cost-effectiveness.

Forward osmosis is a membrane-based technology that separates clean water from contaminants using a semi-permeable membrane. Microwave-assisted treatment uses microwave energy to heat and evaporate water, leaving behind concentrated brine and contaminants. UV photocatalysis breaks down organic pollutants and removes contaminants. Biomass electrochemical systems (BES) use microbial electrochemical systems to treat produced water. ZVI nanoparticles inject nanoscale iron particles into water, facilitating their removal.

Electrocution technology has been improved to reduce chemical additives, making it more sustainable and cost-effective. Innovative filtration media like graphene-based materials and nanocomposite membranes are being developed to enhance contaminant removal. Combining multiple treatment techniques, such as electrocoagulation followed by membrane filtration, has improved treatment efficiency. Ionic liquids are being explored for extracting and separating valuable components from produced water. Membranes inspired by natural biological systems are under development to selectively separate water and contaminants while allowing specific ions or molecules to pass. The use of nanoparticles and nanomaterials for contaminant removal and water treatment in produced water is a rapidly evolving area of research. Future oilfield produced water treatment technologies are demonstrated in Figure 16.

Figure 16. Future produced water treatment technology.

Macro-porous polymer extraction (MPPE) technology offers potential for future produced water management due to its zero-pollutant discharge and energy savings compared to thermal alternatives. However, progress is needed to minimize the high cost. To maximize produced water treatment, a hybrid system can be formed using two or more methods. Future technology may treat produced water electrochemically, which is cheaper, greener, and does not use chemicals or produce secondary waste. It can effectively remove biological pollutants, create and store energy, and help recover valuable elements from produced water without harming the environment [137,180]. Mechanical vapor compression (MVC), membrane distillation (MD), and forward osmosis (FO) technologies can treat high-salinity produced water for reuse, while geothermal energy can reduce energy costs [224]. Photocatalysis can be used to reduce total organic carbon (TOC), degrade organic contaminants, increase biodegradability, and reduce water toxicity [225]. Modernizing membrane materials and optimizing cleaning methods can be effective in purifying produced water [11].

CO_2 decarbonation can change the pH of softened water to 8.4–8.6 and recover economically valuable elements from oilfield water [226]. Long-term, cost-effective NaCl and other salt management strategies are needed for sustainably produced water management. Pervaporative distillation is a promising desalination method for produced water treatment when paired with solar energy or waste heat [148]. Electrochemical coagulation (EC) uses more energy but is more efficient in treating produced water [215].

8. Conclusions

Treatment technology for PW is sought due to its toxicity, environmental problems, and water constraints. Over the last two decades, O&G has been removed from PW more than any other component. Modern PW research encompasses all sectors, especially in water-scarce countries with harsh or cold climates. More than 200 technical articles from throughout the world were examined, analyzed, and included in this study. Below are our findings and suggestions:

- The identification of constituents in PW makes it difficult to predict effective treatment methods. The scaling envelope and system performance for produced water are relatively unknown, making treatment technology selection difficult or ineffective. The market's dynamic nature and new regulations increase the need for solutions to treat oilfield water, which has higher contaminants content. Off-the-shelf technologies can be developed for this purpose, driven by economics, flexibility, and real-time optimization. Analytical data are crucial for formulating treatment and optimization, but unreliable data are a concern as regulations tighten;
- Potentially sustainable PW is threatened by both nonconventional energy sources and an inadequate data repository. Contrary to common belief, shutting down oil and gas plants has resulted in a major reduction in water production. Based on WOR and limited test results, the actual volume of produced water is calculated. Oil and gas companies are hesitant to treat PW for beneficial reuse since meeting strict usage requirements is more expensive than simply disposing of it;
- PW's complexity needs coordinated treatment to maximize water quality and save on costs. Thermal treatment cleans very polluted water, especially saline streams, with long life cycles. Membrane filtration technology has increased in popularity because it may solve conventional treatment methods' high costs, harmful chemical use, requirement for specialized equipment and design, and undesired byproducts. Membrane filtering PW's complex matrix requires advanced planning and more research on fouling solutions;
- Many physical, chemical, and biological approaches can comply with PW's pollutants and reuse. However, PW's complexity has prohibited separate technologies from converting it for reuse or disposal. More research is needed to determine the weighting factor of each component to the total risk, resulting in the best management plan;
- Chemical selection in oil and gas operations should consider non-organic carbon compounds, as removal is costly and difficult. Commercial treatment technologies are tailored to specific needs or compounds, making compact systems essential for sustainable treatment. These systems can address a wide range of pollutants while using minimal resources. No single technology can provide all desired effluent characteristics, so hybrid treatment systems may be used in series to meet regulatory limits. Environmental remediation purposes should be a key decision factor when choosing treatment technologies.

It is crucial to encourage the reuse of PW, particularly in areas experiencing water stress. We feel this comprehensive study will allow for further research on treating PW using the adsorption process and the proper disposal of treated water in academia and industry.

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