



Review

Review of technologies for oil and gas produced water treatment

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ABSTRACT

Produced water is the largest waste stream generated in oil and gas industries. It is a mixture of different organic and inorganic compounds. Due to the increasing volume of waste all over the world in the current decade, the outcome and effect of discharging produced water on the environment has lately become a significant issue of environmental concern. Produced water is conventionally treated through different physical, chemical, and biological methods. In offshore platforms because of space constraints, compact physical and chemical systems are used. However, current technologies cannot remove small-suspended oil particles and dissolved elements. Besides, many chemical treatments, whose initial and/or running cost are high and produce hazardous sludge. In onshore facilities, biological pretreatment of oily wastewater can be a cost-effective and environmental friendly method. As high salt concentration and variations of influent characteristics have direct influence on the turbidity of the effluent, it is appropriate to incorporate a physical treatment, e.g., membrane to refine the final effluent. For these reasons, major research efforts in the future could focus on the optimization of current technologies and use of combined physico-chemical and/or biological treatment of produced water in order to comply with reuse and discharge limits.

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Abbreviations: BAF, biological aerated filter; BOD, biochemical oxygen demand; Bq/l, becquerel per liter; BTEX, benzene, toluene, ethylbenzene, and xylenes; COD, chemical oxygen demand; CAPEX, capital expenses; FWS, free-water surface; MF, microfiltration; MBR, membrane bioreactor; mg/L, milligram per liter; MWCO, molecular weight cut-off; NF, nanofiltration; O&G, oil and grease; PAHs, polycyclic aromatic hydrocarbons; ppb, parts per billion; ppm, part per million; RO, reverse osmosis; SBR, sequencing batch reactor; SMZ, surfactant-modified zeolite; SS, suspended solids; SSF, subsurface flow; TDS, total dissolved solids; TPH, total petroleum hydrocarbons; UF, ultrafiltration; VSEP, vibration shear enhanced process.

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1. Introduction

The significance of oil and natural gas in modern civilization is well known. Nevertheless, like most production activities, oil and gas production processes generate large volumes of liquid waste. Oilfield wastewater or produced water contains various organic and inorganic components. Discharging produced water can pollute surface and underground water and soil.

The permitted oil and grease (O&G) limits for treated produced water discharge offshore in Australia are 30 mg/L (milligram per liter) daily average and 50 mg/L instantaneous [1]. Based on United States Environmental Protection Agency (USEPA) regulations, the daily maximum limit for O&G is 42 mg/L and the monthly average limit is 29 mg/L [2]. As regards the significant matter of environmental concern, many countries have implemented more stringent regulatory standards for discharging produced water. The monthly average limits of O&G discharge and chemical oxygen demand (COD) prescribed by the Peoples Republic of China are 10 and 100 mg/L, respectively [3]. Based on the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention), the annual average limit for discharge of dispersed oil for produced water into the sea is 40 mg/L [4]. On the other hand, because large volumes of produced water are being generated, many countries with oilfields, which are also generally water-stressed countries, are increasingly focusing on efforts to find efficient and cost-effective treatment methods to remove pollutants as a way to supplement their limited fresh water resources. Reuse and recycling of produced water include underground injection to increase oil production, use for irrigation, livestock or

wildlife watering and habitats, and various industrial uses (e.g., dust control, vehicle washing, power plant makeup water, and fire control) [5].

In order to meet environmental regulations as well as reuse and recycling of produced water, many researchers have focused on treating oily saline produced water. Oil content and salinity of produced water from offshore and onshore activities can be reduced through various physical, chemical, and biological methods. In offshore extraction facilities due to space constraints, compact physical and chemical treatment technologies are preferred. However, as capital cost of physical methods and cost of chemicals for chemical treatment of hazardous sludge is high, the application of these methods is limited. Current methods cannot remove minute suspended oil and/or hazardous dissolved organic and inorganic components. On the other hand, biological treatment is a cost-effective method for removing dissolved and suspended compounds from oilfield wastewater in onshore extraction facilities.

The main purpose of this review is:

- (a) To introduce oil and gas produced water origin and characteristics,
- (b) To summarize current technologies available to treat offshore and onshore produced water,
- (c) To focus on combined methods to improve effluent characteristics,
- (d) To discuss advantages and drawbacks of the various treatment methods, and

(e) Discuss future development needs to meet discharge, reuse, and recycle standards.

1.1. Origin of produced water

Naturally occurring rocks, in subsurface formations are generally permeated by different underground fluids such as oil, gas, and saline water. Before trapping hydrocarbon compounds in rocks, they were saturated with saline water. Hydrocarbons with lower density migrated to trap locations and displaced some of the saline water from the formation. Finally, reservoir rocks absorbed saline water and hydrocarbons (oil and gas). There are three sources of saline water:

- Flow from above or below the hydrocarbon zone,
- Flow from within the hydrocarbon zone,
- Flow from injected fluids and additives resulting from production activities.

The last category is called “connote water” or “formation water” and becomes produced water when saline water mixed with hydrocarbons comes to the surface [5].

In oil and gas production activities, additional water is injected into the reservoir to sustain the pressure and achieve greater recovery levels. Both formation water and injected water are produced along with hydrocarbon mixture. At the surface, processes are used to separate hydrocarbons from the produced fluid or produced water [6].

1.2. Global onshore and offshore produced water production

Global produced water production is estimated at around 250 million barrels per day compared with around 80 million barrels per day of oil. As a result, water to oil ratio is around 3:1 that is to say water cut is 70%. The global water cut has risen since a decade ago and continues to rise. Produced water is driven up by maturing of old fields but driven down by better management methods and the introduction of new oil fields [7,8].

Fig. 1 gives an estimate of onshore and offshore produced water production since 1990, and forecast in 2015.

1.3. Factors affecting production volume of produced water

Reynolds and Kiker [9] evaluated different factors that can affect the amount of produced water production on the life of a well:

1. Method of well drilling: a horizontal well can produce at a higher rate than a vertical well at similar drawdown, or can produce similar production rate at lower drawdown.
2. Location of well within homogeneous or heterogeneous reservoirs: for homogeneous reservoirs, use of horizontal wells reduces water production but in homogeneous reservoirs, the increase in production of horizontal versus unstimulated vertical wells is proportional to the reservoir's area contacted by the wells.
3. Different types of completion: the open hole method permits testing of drilling zones and avoids drilling into water. On the other hand, the perforated completion method offers a much higher degree of control since the interval can be perforated and tested.
4. Single zone and commingled: most wells are initially completed in a single zone. As oil rate declines because of maturing of the well, other zones may be opened to maintain the oil production rate, as a result water production too increases.
5. Type of water separation technologies: different methods are used to reduce costs of lifting and/or water handling for wells that produce large quantities of saline water. These methods are water shut-off treatment using gelled polymers, reducing beam pump lifting costs, power options to reduce electrical costs and separation technologies.
6. Water injection or water flooding for enhancing oil recovery: the aim of water flooding is getting the well-treated water to the oil level to increase production rate. Because of water flooding, an increasingly higher percentage of water is produced. As a flood progresses, the volume of required water for injection increases. In this case, makeup water with suitable chemical characteristics is necessary. The poor quality of treated produced water, or makeup enables sealing, clay swelling, and brine incompatibilities.
7. Poor mechanical integrity: many water entries are caused by mechanical problems of the casing holes caused by corrosion or wear, and splits caused by flows; excessive pressure can allow unwanted reservoir fluids to enter the casing and increase water production.
8. Underground communications: underground communications problems happen near wellbores or reservoirs. Both these problems generate increase in produced water. Near wellbore problems are the channels behind casing, barrier breakdowns, and completions into or near water. Reservoir-related problems are coning, cresting, channeling through higher permeability zones or fractures, and fracturing out of zone.

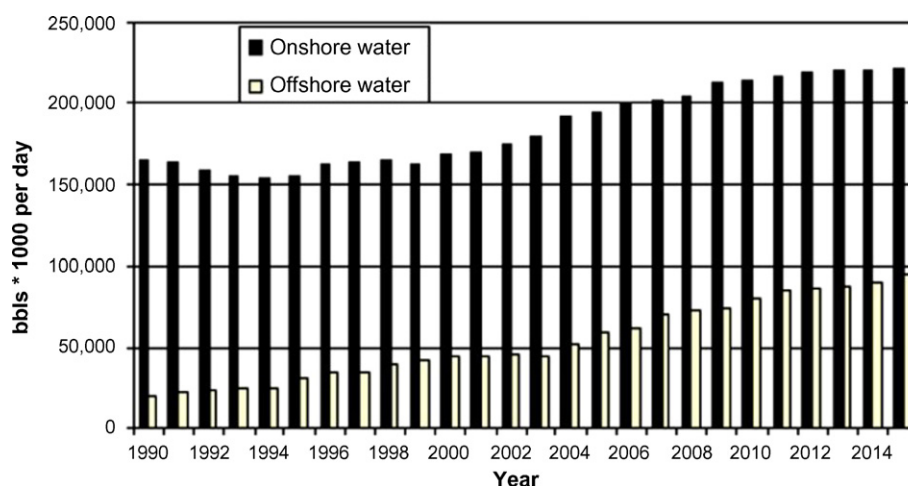


Fig. 1. Global onshore and offshore water production. Reprinted with permission from Ref. [7].

1.4. Characteristics of produced water

Produced water is a mixture of organic and inorganic materials. Some factors such as geological location of the field, its geological formation, lifetime of its reservoirs, and type of hydrocarbon product being produced affect the physical and chemical properties of produced water [5].

Produced waters characteristics depend on the nature of the producing/storage formation from which they are withdrawn, the operational conditions, and chemicals used in process facilities. The composition of produced water from different sources can vary by order of magnitude. However, produced water composition is qualitatively similar to oil and/or gas production [10].

The major compounds of produced water include:

- (A) Dissolved and dispersed oil compounds,
- (B) Dissolved formation minerals,
- (C) Production chemical compounds,
- (D) Production solids (including formation solids, corrosion and scale products, bacteria, waxes, and asphaltenes),
- (E) Dissolved gases [11].

1.4.1. Dissolved and dispersed oil compounds

Oil is a mixture of hydrocarbons including benzene, toluene, ethylbenzene, and xylenes (BTEX), naphthalene, phenanthrene, dibenzothiophene (NPD), polyaromatic hydrocarbons (PAHs) and phenols. Water cannot dissolve all hydrocarbons, so most of the oil is dispersed in water [6].

The amounts of dissolved and suspended oil present in produced water (prior to treatment) are related to following factors:

- Oil composition,
- pH, salinity, TDS (total dissolved solids), temperature,
- Oil/water ratio,
- Type and quantity of oilfield chemicals,
- Type and quantity of various stability compounds (waxes, asphaltenes, fine solids) [11].

1.4.1.1. Dissolved oil. The water-soluble organic compounds in produced water are polar constituents and found distributed between the low and medium carbon ranges. Organic acids such as formic acid and propionic acid are typically in produced water. pH and temperature increase soluble organics in produced water. Pressure enhances dissolved organic compound concentration slightly. Temperature alters the relative ratio of carbon ranges within the water. Soluble compounds do not increase total dissolved organics in produced water. In addition, salinity does not significantly affect the dissolved organics in produced water [12]. The amounts of oil soluble in produced water depend on type of oil, volume of water production, artificial lift technique, and age of production [13]. Aromatic compounds which are the most important chemicals contributing to natural environments toxicity cannot be removed efficiently by oil/water separation techniques. Besides, by increasing alkylation of components, the concentration of naphthalene, phenanthrene, dibenzothiophene and their C1–C3 alkyl homologous and alkylated phenols reduces [14]. In some sites, concentrations of these components are relatively high [15]. BTEX and phenols are the most soluble compounds in produced water [6]. Aliphatic hydrocarbons, phenols, carboxylic acid, and low-molecular weight aromatic compounds are included as soluble oil compounds in produced water [13].

1.4.1.2. Dispersed oil. Dispersed oil consists of small droplets of oil suspended in the produced water. The amount of dispersed oil in produced water depends on the density of oil, the shear history

of the droplet, the amount of oil precipitation and interfacial tension between the water and oil [13]. PAHs and some of the heavier alkyl phenols are less soluble in produced water and are present as dispersed oil [6]. The concentration of PAHs and C6–C9 alkylated phenols is strongly correlated to dispersed oil content of produced water [16].

1.4.2. Dissolved formation minerals

Inorganic dissolved compounds in produced water include anions and cations, heavy metals, and radioactive materials. Produced water contains a wide range of both cations and anions. All of them have similar patterns of concentration for different metals [16].

1.4.2.1. Cations and anions. Cations such as Na^+ , K^+ , Ca^{2+} , Mg^{2+} , Ba^{2+} , Sr^{2+} , Fe^{2+} and anions such as Cl^- , SO_4^{2-} , CO_3^{2-} , HCO_3^- affect produced water chemistry in terms of buffering capacity, salinity, and scale potential [11]. Salinity is due to dissolved sodium and chloride and is less contributed by calcium, magnesium, and potassium. Salt concentration of produced water may vary from a few parts per million (ppm) to about 300,000 mg/L [1,17], 1000–250,000 mg/L [18]. Sulfate concentration in produced water is lower than seawater. In some sites that use seawater for oil enhancing recovery, sulfate concentration is high [1].

1.4.2.2. Heavy metals. Heavy metal concentrations in produced water depend on age of the wells and formation geology [19]. Produced water contains trace quantities of various heavy metals such as cadmium, chromium, copper, lead, mercury, nickel, silver, and zinc [11].

1.4.2.3. Naturally occurring radioactive materials (NORM). The source of radioactivity in scale is from radioactive ions, primarily radium that is co-precipitated from produced water along with other types of scales. Barium sulfate is the most common scale co-precipitated [13]. ^{226}Ra and ^{228}Ra are the most abundant NORM in produced water [19]. There is a strong correlation between concentrations of barium and radium isotopes [20]. In the North Sea, concentrations of ^{226}Ra and ^{228}Ra in samples ranged from below the detectable detection limits 0.3–1.3 becquerel per liter (Bq/L) up to 16 and 21 Bq/L, respectively [21].

1.4.3. Production chemical components

During the oil and gas production process, some chemicals are added to treat or prevent operational problems. Treatment chemicals (production treating, gas processing, and stimulation) and production treating chemicals (scale and corrosion inhibitors, biocides, emulsion breakers, antifoam and water treatment chemicals) are used in these processes [13]. A wide range of polar and charged molecules like linear alkylbenzen sulfonate (LAS), alkyl dimethylbenzylammonium compounds, 2-alkyl-1-ethylamine-2-imidazolines, 2-alkyl-1-[N-ethylalkylamide]-2-imidazolines, and a-di-[alkyl dimethylammonium-ethyl] ether have been identified and characterized in commercial formulation and/or in the water produced in the North Sea oilfields [22]. The concentration of production chemicals in produced water is as low as 0.1 ppm [5].

1.4.4. Production solids

Production solids are a wide range of materials including formation solids, corrosion and scale products, bacteria, waxes, and asphaltenes. In anoxic produced water, sulfides (polysulfides and hydrogen sulfide) are generated by bacterial reduction of sulfate [1]. Because of different toxic chemicals in produced water, few microorganisms can survive. Biological analysis indicates that there are 50–100 cells of microorganisms per mL, in which the majority

Table 1
Constituents (mg/L) in natural gas produced waters (pH is presented in standard units) [132].

Parameter	Minimum value	Maximum value	Parameter	Minimum value	Maximum value
pH ^a	4.4	7.0	Iron ^a	ND	1100
pH ^b	3.1	6.47	Iron ^b	39	680
Conductivity ^a (umhos/cm)	4200	180,000	Lead ^b	<0.2	10.2
Conductivity ^b (umhos/cm)	136,000	586,000	Lithium ^b	18.6	235
Alkalinity ^b	0	285	Magnesium ^a	0.9	4300
TDS ^a	2600	310,000	Magnesium ^b	1300	3900
TDS ^b	139,000	360,000	Manganese ^a	0.045	6.5
TSS ^a	14	800	Manganese ^b	3.59	63
TSS ^b	8	5484	Nickel ^a	ND	0.02
BOD ₅ ^a	75	2870	Nickel ^b	<0.08	9.2
COD ^a	2600	120,000	Potassium ^b	149	3870
Aluminum ^a	ND	0.4	Silver ^b	0.047	7
Aluminum ^b	<0.50	83	Sodium ^a	520	45,000
Arsenic ^a	0.004	1	Sodium ^b	37,500	120,000
Arsenic ^b	<0.005	151	Strontium ^a	–	6200
Barium ^a	ND	26	Sulfate ^a	<0.1	47
Barium ^b	9.65	1740	Sulfate ^b	ND	19
Boron ^a	ND	56	Tin ^a	ND	1.1
Bromide ^b	150	1149	Zinc ^a	ND	0.022
Cadmium ^a	ND	0.015	Zinc ^b	<0.02	5
Cadmium ^b	<0.02	1.21	TOC ^a	67	38,000
Calcium ^a	ND	25,000	Surfactants ^b	0.08	1200
Calcium ^b	9400	51,300	Benzene ^a	1.8	6.9
Chloride ^a	1400	190,000	Benzene ^c	<0.010	10.3
Chloride ^b	81,500	167,448	Toluene ^a	0.857	3.37
Chromium ^a	ND	0.03	Toluene ^c	<0.010	18
Copper ^a	ND	0.02	Oil/grease ^a	6	60
Copper ^b	<0.02	5	Oil/grease ^b	2.3	38.8

^a [133].

^b [134].

^c [135].

of microorganisms are aerobic Gram-positive bacteria [23]. Bacteria can clog or cause corrosion of equipment and pipelines [5]. Some inorganic crystalline substances such as SiO₂, Fe₂O₃, Fe₃O₄, and BaSO₄ are found in the suspended solids (SS) in produced water [24].

1.4.5. Dissolved gases

CO₂, O₂, and H₂S are common gases included in produced water [11].

1.4.6. Produced water from gas fields

In gas fields, water injection is not utilized; therefore, the produced waters are mixture of formation water and condensed water. Their chloride content varies from almost those of fresh water to salty formation water with chloride concentration about 14 times that of seawater. Its acidity is greater than that of produced water from oilfields [16].

The volume of produced water from gas field is less than in oilfields. A wide range of gas treatment chemicals is used in gas fields

Table 2
Summary of oilfield-produced water parameters in world [136].

Parameter	Values	Heavy metal	Values (mg/L)
Density (kg/m ³)	1014–1140	Calcium	13–25800
Surface Tension (dynes/cm)	43–78	Sodium	132–97000
TOC (mg/L)	0–1500	Potassium	24–4300
COD (mg/L)	1220	Magnesium	8–6000
TSS (mg/L)	1.2–1000	Iron	<0.1–100
pH	4.3–10	Aluminum	310–410
Total oil (IR; mg/L)	2–565	Boron	5–95
Volatile (BTX; mg/L)	0.39–35	Barium	1.3–650
Base/neutrals (mg/L)	<140	Cadmium ^a	<0.005–0.2
(Total non-volatile oil and grease by GLC/MS) base (μg/L)	275	Chromium	0.02–1.1
Chloride (mg/L)	80–200,000	Copper	<0.002–1.5
Bicarbonate (mg/L)	77–3990	Lithium	3–50
Sulfate (mg/L)	<2–1650	Manganese	<0.004–175
Ammoniacal nitrogen (mg/L)	10–300	Lead ^a	0.002–8.8
Sulfite (mg/L)	10	Strontium	0.02–1000
Total polar (mg/L)	9.7–600	Titanium	<0.01–0.7
Higher acids (mg/L)	<1–63	Zinc ^a	0.01–35
Phenols (mg/L)	0.009–23	Arsenic ^a	<0.005–0.3
VFA's (volatile fatty acids) (mg/L)	2–4900	Mercury	<0.001–0.002
		Silver ^{a,b}	<0.001–0.15
		Beryllium	<0.001–0.004

^a Analyzed by atomic absorption.

^b Value should be regarded as a minimum due to poor solubilities.

including methanol, ethylene glycol, and triethylene glycol. About one-third of these chemicals are discharged in produced water [1]. Volatile components concentrations in produced water from gas fields are higher than those in produced water from oilfields [19]. Table 1 shows concentrations of constituents in produced water from gas fields.

1.4.7. Produced water from oil fields

Table 2 summarizes a range of produced water characteristics in different oilfields in the world. The data show ranges of pollutants and constituents that are present in produced water.

1.5. Fate and impact of produced water discharge

Produced water from oil and gas industries often is permitted to be discharged to the environment [25]. Water's toxicity and organic loading [11] can generally characterize the impact of discharging produced water into the sea.

Effects of produced water components on the environment are as follows.

1.5.1. Salinity

Environmental effect of produced water salts can occur in all regions where oil and gas have been produced [26]. It is as a major contributor of toxicity [1].

1.5.2. Dispersed and soluble oil

Dispersed oil and droplets do not precipitate at the bottom of sea but rise to the surface of water. Volatile and/or toxic compounds evaporate. These materials increase the biochemical oxygen demand (BOD) of the affected water [13]. Nonpolar organics from different sources of produced water are consistently toxic [27]. The major compounds toxic to freshwater animals are hydrogen sulfide and hydrocarbons, found at low-salinity concentrations of produced water [1]. Produced water toxicity can be expressed as acute or chronic toxicity. Acute toxicity can be measured by the LC50 test, but long-term effects or chronic toxicity are more difficult to quantify [11].

The following are the methods to assess the risk that produced water causes or may cause to the environment:

- Testing substances on animals or other biota,
- Scientific monitoring of discharge [6],
- Theoretical modeling of produced water discharge [28].

1.5.3. Treating chemicals

Water-soluble production chemicals do not have toxicity effects in the aqueous phase compared to oil soluble production chemicals at the same concentration. However, some production chemicals can increase partitioning of oil compounds into the aqueous phase at high concentrations [29]. Treatment chemicals can precipitate and accumulate in marine sediments [30].

1.5.4. Heavy metals

The concentration of heavy metals in produced water is often higher than in seawater. Dilution of metals concentration is very rapid [13]. Heavy metal toxicity is less than nonpolar organics in produced water [27] and does not have an adverse affect on marine environment [13].

1.5.5. Radionuclides

Presence of radionuclides in produced water depends upon the source and geological formation [13]. Risks associated with discharge of produced water containing radionuclides on animals and the marine environment are very small [31].

2. Produced water management

Produced water is considered an oilfield waste. Whether waste or commodity, produced water management has a cost. For managing produced water, a three-tiered pollution prevention hierarchy is followed:

1. Employing technologies to minimize produced water production,
2. Reuse and recycling,
3. If neither of these tiers is practical, disposal is the final option [32].

Some of the options available to oil and gas operators for produced water management proposed by Arthur et al. [33] are as follows:

1. Injection: injection of produced water into the same formation from which the oil is produced or handle to another formation.
2. Discharge: treatment of produced water to meet onshore or off-shore discharge regulations.
3. Reuse in oil and gas operation: treat the produced water to meet the quality required to use it for usual oil and gas fields operations.
4. Consume in beneficial use: produced water treatment to meet to quality required for beneficial uses such as irrigation [34], rangeland restoration, cattle and animal consumption, and drinking water [35].

Treatment of produced water is an effective option for produced water handling. Treatment of produced water has the potential to be a harmless and valuable product rather than a waste. The general objectives for operators for treating produced water are as follows [33]:

1. De-oiling: removing dispersed oil and grease,
2. Soluble organics removal,
3. Disinfection,
4. SS removal: removing of suspended particles and sand,
5. Dissolved gas removal: removing of light hydrocarbon gases, carbon dioxide, and hydrogen sulfide,
6. Desalination: removing dissolved salts,
7. Softening: removing excess water hardness,
8. Miscellaneous: removing NORM.

Many separate and combined physical, chemical, and biological methods are proposed for produced water treatment.

2.1. Physical treatment

2.1.1. Adsorption of dissolved organics on activated carbon, organoclay, copolymers, zeolite, resins

Organic compounds of produced water (and some heavy metals) adhere to porous media of carbon surfaces. After a few runs, the wet air oxidation process [11] can regenerate activated carbon. Activated carbon can remove soluble BTEX but organoclay can remove insoluble free hydrocarbons that contribute to total petroleum hydrocarbons (TPH) and O&G measurement. Organoclay is produced by combining sodium montmorillonite clay with a cationic quaternary amine salt. When organoclay is used in conjunction with activated carbon, hydrocarbon concentration falls below water quality standards [36]. Copolymer beads are prepared based on methylmethacrylate (MMA) and divinylbenzene (DVB) by suspension polymerization. These copolymers can reduce oil content of produced water to around 85% [37].

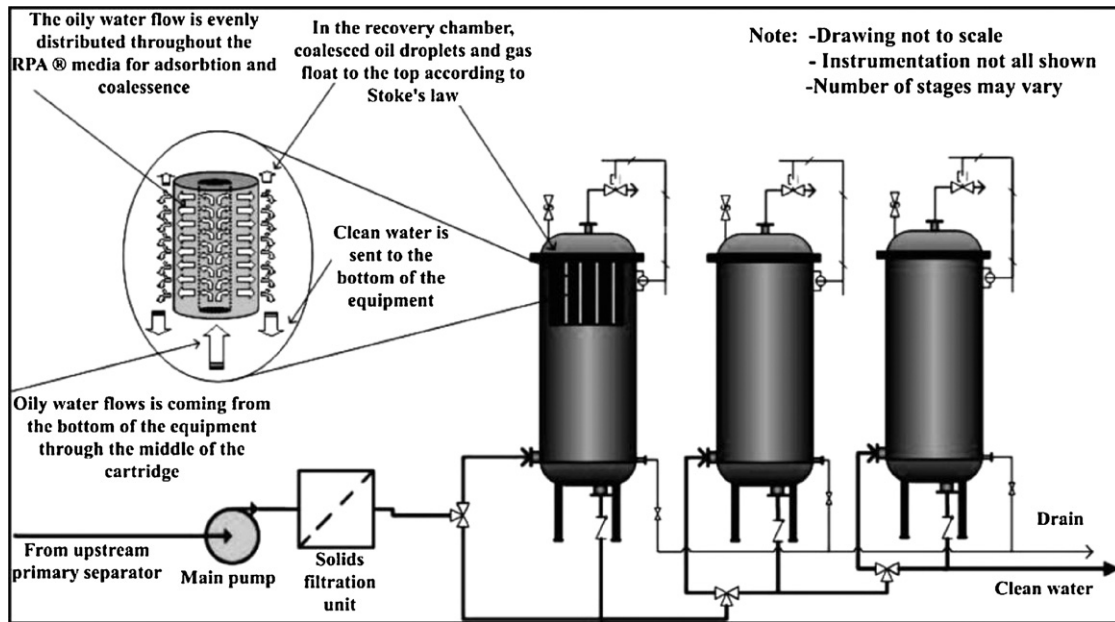


Fig. 2. Process flow diagram of TORR technology. Reprinted with permission from Ref. [46].

Zeolites are often used as ion-exchange resins. Use of hydrophobic zeolite pellets in a fixed bed to adsorb dissolved organic compounds in produced water is proposed [11]; on the other hand, Mitchell et al. [38] proposed a resin-filled column to remove soluble organic compounds. In both methods, acid backwash and solvents can regenerate the adsorbers.

Performance of adsorbers is affected by

- Temperature and pH,
- Suspended oil,
- Low heavy metal concentration and organic–metal complex,
- Dissolved contaminants (organics chemicals),
- High salinity [11].

Suspended particles in raw produced water plug media and reduce removal efficiency. On the other hand, chemical wastes from regeneration of adsorbers are the new problems added by these methods [39].

Janks and Cadena [40] used “tailored” zeolites, to remove BTEX from saline produced water. They were made by adsorbing neutralized amines onto natural zeolites. The projected process removal efficiency was 70–85%.

In a grafted process with $-\text{COOH}$, $=\text{NH}$, and $-\text{OH}$ groups, surfaces of PET fibers were modified from oleophilic to hydrophilic. The modified fibers were used to treat oilfield-produced water. Treated effluent characteristics were as follows: $\text{O\&G} < 2.4 \text{ mg/L}$, $\text{SS} < 2 \text{ mg/L}$. The results were comparable with currently popular

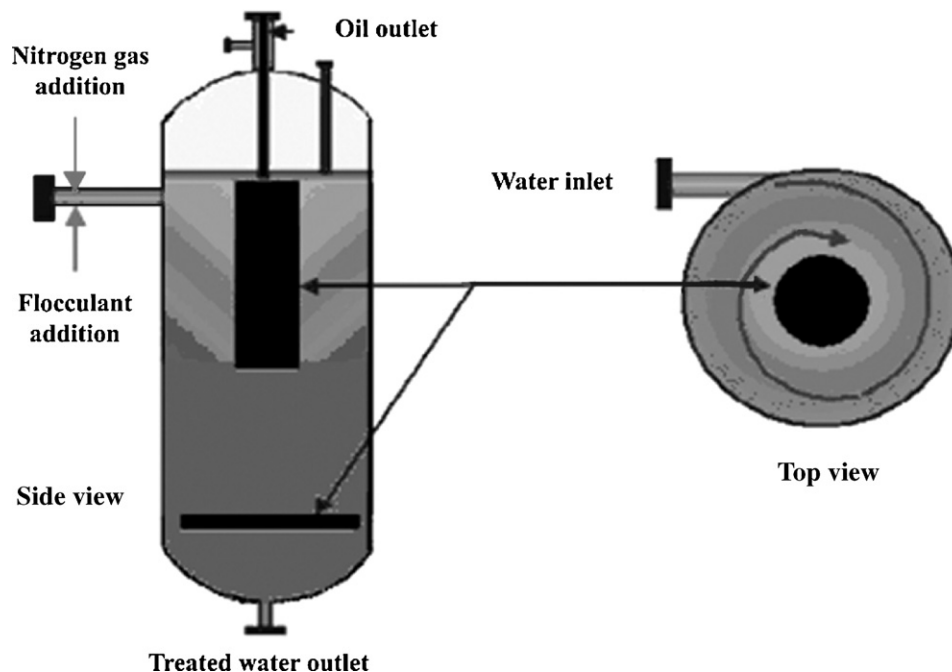


Fig. 3. Illustration of the Epcon CFU unit. Reprinted with permission from Ref. [49].

walnut medium. The effluent can be used for water flood or water injection in enhanced oil recovery processes [41].

In a series adsorption process consisting of Crudersorb technology and polymeric resins, offshore-produced water was treated to reduce O&G concentration levels to less than 29 ppm. Crudersorb removes suspended and dispersed oil droplets and resin removes dissolved hydrocarbons, aliphatic carboxylic acids, aromatic carboxylic acids, and phenolic compounds [42].

A hydrophilic fiber ball medium that was developed through surface modification methods, could remove O&G of produced water from alkaline/surfactant/polymer flooding (ASP produced water) efficiently [43].

In a proposed system consisting two beds of strong acid ion-exchange resin in series, oil-free produced water could be treated to remove calcium and magnesium. The system worked well with TDS of less than 50,000 ppm. The chemical structure of strong-acid-cation-exchange resin is sulfonated copolymer of styrene and divinylbenzene. When the TDS of produced water is higher than 50,000 ppm, sodium competes with calcium and magnesium for sites on the resin [44].

Doyle et al. [45] tested the combination of ET Ventures' ET #1 (a modified polymer or bentonite or an organoclay) and granular activated carbon in packed bed adsorption column. The treatment system could remove hydrocarbons consistently and effectively. Results showed that the system reduced total petroleum hydrocarbon and O&G to non-detectable levels, and reduced soluble hydrocarbons: benzene, ethylbenzene, toluene, and xylene too to barely detectable levels. The main drawback of adsorption systems is the need for frequent regeneration of materials and the generation of waste.

The EARTH Canada Corporation has developed a technology called Total Oil Remediation and Recovery (TORR™) to remove and recover dispersed oil in water 2 μm and larger. The technology is a multi-stage adsorption and separation system. An adsorbent media, the Reusable Petroleum Adsorbent (RPA®, the media) removes large and small oil droplets. This material is a polyurethane-based, oleophilic, hydrophobic, nontoxic, media coalescing agent. In the process of adsorption, the media continuously adsorbs the oil emulsions, coalesces, and desorbs them into larger oil droplets. In the recovery chamber, oil droplets desorbed by the media float to the top of the chamber in accordance with Stoke's Law [46].

Fig. 2 shows process flow diagram of TORR technology.

Li et al. [47] studied removal of oil from produced water by use of modified porous ceramics filtration media (MPCFM) in a fixed bed column. Porous filtration media was modified with containing hydrogen silicone oil (CHSO). Results showed that reducing filter-

ing velocity, increasing oil content, and thickness of filtering layers enhanced oil removal efficiency.

2.1.2. Sand filters

Adewumi et al. [48] proposed a three-step pretreatment before sand filtering for removing metals from produced water. The system consisted of the following:

- pH adjustment: to initiate oxidation reaction,
- Aeration unit: to increase oxygen concentration for reaction,
- Solid separation unit: sufficient retention time for settling of precipitated solids,
- Sand filtration: removing fine solids that could not settle.

Results of different runs by the system showed that more than 90% iron could be removed.

2.1.3. Cyclones

The Epcor compact floatation unit (CFU) is a vertical separator vessel. The system is capable of separating three-phases, namely water/oil/gas by centrifugal force and gas-flotation. Treated water exits the vessel at the bottom and a pipe suspended from the top of vessel extracts gas, oil, and some water. Fig. 3 illustrates the unit. The Epcor unit removal efficiency for dispersed oil was only 50–70% [49].

In offshore installations because of space constraints, compact systems with small and light characteristics are favorable. Seureau et al. [50] designed a three-phase cyclonic separator to remove solids and oil from offshore-produced water. The system combines the functional characteristics of both desanding and de-oiling hydrocyclones.

Treatment of produced water by polymer flooding is more difficult than that by water flooding, because of the high viscosity and very small oil droplet size in the former. A double cone air sparged hydrocyclone (DCASH) was designed to solve the problem. This system used air bubbles and centrifugal force to enhance removal efficiency of oil droplets [51].

Deng et al. [52] proposed crossflow oil–water separator for polymer flooding. The system consisted of different coalescence and separator sections. Sludge was removed from the bottom and oil and gas was separated from the top. Oil concentration in treated produced water fell to less than 100 ppm. Fig. 4 shows a schematic of the system.

Van den Broek and Van der Zande [53] compared oil removal efficiencies of different de-oiling systems. Their rankings with respect to performance of three physical separators were: centrifuges, hydrocyclones, and plate separators. Besides the low removal effi-

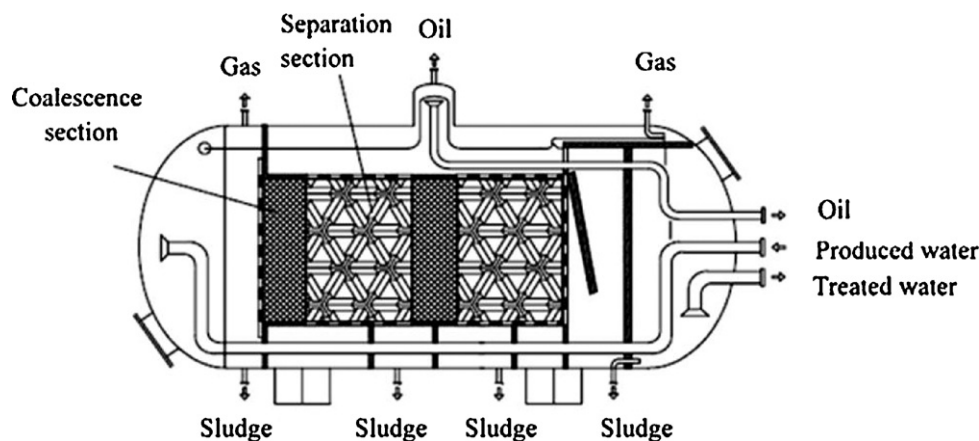


Fig. 4. Schematic illustration of crossflow oil–water separator. Reprinted with permission from Ref. [52].

ciency of these systems, dissolved and hazardous components could not be removed.

2.1.4. Evaporation

Some researchers proposed evaporation methods for treating saline wastewater containing oil components [54]. Vertical tube, falling film, and vapor compression evaporation are effective methods for produced water treatment because they:

1. Eliminate physical and chemical treatments so no chemical sludge is produced, and costs of waste and life cycle are lowered.
2. Require less maintenance materials and maintenance labor.
3. Reduce the amount of produced water de-oiling equipment required.
4. Increase Once Through Steam Generators (OTSG) feed-water quality, and improve OTSG reliability [55]. However, due to presence of high impurity levels of solid salts the reuse of these materials is impossible [56].

Becker [57] proposed wastewater distillation using two-proprietary new designed systems (PNDS) that recover over 95% of the energy required to distill water as follows:

1. New mechanical vapor recompression (MVR) system to recycle produced water into distilled water.
2. Waste steam to accomplish the same.

In commercial scale applications, more than 95% of the operating cost of distillation is energy. Thus the proposed PNDS reduces the total operating cost by 90%.

2.1.5. Dissolved air precipitation (DAP)

Thoma et al. [58] reported the use of bubble generation by dissolved air precipitation for use in solvent sublation bubble columns. Solvent sublation is a non-foaming adsorptive bubble separation. In the DAP process; air was saturated into water at 480–820 kPa in a packed column separator. By releasing the pressure through a valve into the water column, air was precipitated and formed bubbles of 60–100 mm diameter. In a pilot-scale with a simulated produce water using aliphatic and aromatic hydrocarbons, the level of removal of dissolved octane, micro-dispersed decane, dissolved ethylbenzene achieved was 95%, 75%, and 40%, respectively.

2.1.6. C-TOUR

C-TOUR, a patented technology, used liquid condensate as extraction liquid for dissolved components in produced water.

The C-TOUR process included the following steps:

- Injection of condensate stream from the production process into produced water. Condensate stream is available from the scrubbers in the gas compression train.
- Contact time between condensate and water.
- Removing contaminated condensate from water.
- Contaminant condensate is recycled back into original production streams.

In three sets of field trials conducted with the C-TOUR process, removal efficiency of dispersed oil, 2–3 ring PAHs, and NPD was 70%, for C₆, and for C₆ phenols approximately 60%, and for C₄–C₅ phenols 20% [49].

2.1.7. Freeze-thaw/evaporation

Crystal Solutions, LLC, a joint venture of Gas Technology Institute (formerly Gas Research Institute) and BC Technologies used freeze-thaw/evaporation (FTE) technology to treat produced water. The FTE is a process that used naturally occurring temperature

swings to alternately freeze and thaw produced water, concentrating the dissolved solids and creating relatively large volumes of clean water suitable for various beneficial uses [59,60].

2.1.8. Electrodialysis (ED)

Dissolved salts in water are cations and anions. These ions can attach to electrodes with an opposite charge. In ED, membranes are placed between a pair of electrodes. The membranes allow either cations or anions to pass through [33]. This method is suitable for produced water reclamation with low TDS concentrations. Recent results indicate that this approach may be appropriate for reclamation of produced waters with relatively low TDS loads but is unlikely to be cost-effective for treatment of concentrated produced waters [61].

2.2. Chemical treatment

2.2.1. Chemical precipitation

Coagulation and flocculation can be used to remove suspended and colloidal particles, but are not effective for removing dissolved constituents. Lime softening is the usual process for water softening. In the modified hot lime process produced water containing 2000 ppm hardness, 500 ppm sulfides, 10,000 ppm TDS, and 200 ppm oil could be successfully converted to steam generator-quality feed-water. In this process, alkali consumption and sludge production could be reduced by 50% in comparison with conventional hot lime [62,63].

FMA is an inorganic mixed metal (Fe, Mg, and Al) polynuclear polymer. This chemical had good coagulation, de-oiling and scale inhibition properties particularly in produced water of high SS levels of 50–400 mg/L FMA. SS and oil can be removed to levels >92% and 97%, respectively [64]. On the other hand, Houcine in a study [65] used spillsorb, calcite, and lime to remove heavy metals from produced water. Results showed that lime removal efficiency is greater (>95%) than with others and that it was an economical chemical.

In a study on treatment of oil and gas fields produced water, an oxidant, ferric ions, and flocculants were used to remove hydrocarbons, arsenic, and mercury. In this process, the oxidation–reduction potential of the wastewater was controlled by oxidant addition to allow the required arsenic oxidation to occur while maintaining the mercury in elemental form. Results showed that effluent streams had less than about 10 parts per billion (ppb) of mercury (calculated as Hg), less than about 250 ppb, and preferably less than 100 ppb of arsenic (calculated as As), and less than about 40 ppm of TPH [66]. Disadvantages of the process are generation of sludge and increased concentration of metals in effluents.

2.2.2. Chemical oxidation

Chemical oxidation is the usual method for decomposing refractory chemicals in wastewater in which a strong oxidant, catalysts, and irradiation are used (except ozone treatment) [67].

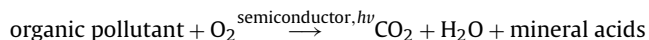
2.2.3. Electrochemical process

In a laboratory pilot-scale plant that included double anodes with active metal, graphite, and iron as cathode and a noble metal content crystal with a large surface, the COD and BOD of oilfield-produced water could be reduced by over 90% in 6 min. In these processes, produced Mn²⁺ ions oxidized and coagulated organic pollutants including bacteria [68].

2.2.4. Photocatalytic treatment

Fujishima and Honda [69] reported the photocatalytic decomposition of water on TiO₂ electrodes. This method can be used for a variety of pollution remediations. The general process for organic

pollutant treatment by photocatalytic method is as follows:



In a proposed process for oilfield-produced water treatment prior to photocatalytic reaction, wastewater pH was increased to 11 by soda addition. After flocculation and settling, the supernatant was filtered. Photocatalytic reaction was carried out in an open reactor with 60 mL previously clarified produced water and adequate amount of photocatalyst-TiO₂. A high-pressure 250 W mercury lamp illuminated the suspension at 298 K. This method could reduce toxicity of produced water [70]. Li et al. [71] found that the COD removal efficiency of produced water by photoelectrocatalytic process was much higher than that of by photocatalytic or electrochemical oxidation. Li et al. [72] also compared treatment of produced water by photocatalysis, electro-oxidation, and photoelectrocatalysis. Results showed that at equivalent doses, photoelectrocatalysis exhibited the greatest capability to reduce genotoxicity, whereas photocatalysis was the least effective and did not cause appreciable change in mutagenicity, but results of both biological and chemical analysis indicated that photoelectrocatalysis was the most effective technology for degradation of oilfield wastewater. In a similar study, Adams et al. [73] utilized a drum reactor with a single pass continuous-flow system for produced water effluents. In this reactor, titanium metal was used as substrate. The reactor drums were irradiated using sunlamp UV tubes. Results showed that hydrocarbon content could be reduced by more than 90% in 10 min.

2.2.5. Fenton process

In a lab-scale study of the combined flocculation settlement-Fenton oxidation adsorption process, COD and oil of produced water were reduced to 100 and 5 mg/L from 2634 to 93.1 mg/L, respectively.

In this process, poly-ferric sulfate was used as the flocculent for a 30-min settling period. The other operational conditions for the process were as follows: pH value 3–4, 30% H₂O₂, of mL/L, Fe³⁺ to H₂O mass ratio of 4%, oxidation time of 120 min, active carbon dose of 4000–5000 mg/L, and adsorption time of 120 min [74].

2.2.6. Treatment with ozone

Morrow et al. [75] proposed ozonolysis for decomposing dissolved organic compounds in produced water. Klasson et al. [76] compared destruction of soluble organics in synthetic and real produced water by sonochemical oxidation and ozone. Sonochemical oxidation could destroy some compounds such as BTEX, but the combination of ozone and hydrogen peroxide did not improve the oxidation of organics to CO₂. Their experiment showed that during 3 days of exposure to ozone nearly all extractable organics could be destroyed.

In addition to the low removal efficiency of chemical oxidation products, high running costs due to the high demand of energy and consumption of chemicals are disadvantages of these methods [67].

2.2.7. Room temperature ionic liquids

McFarlane et al. [77] studied the distribution of polar organic compounds typical of water contaminants associated with oil and gas production between water and nine hydrophobic, room temperature ionic liquids (liquids that contains only ions). Results showed that certain hydrophobic ionic liquids do have an affinity for organic contaminants in aqueous solution. However, practical application of the ionic liquids tested for detection or removal of selected water-soluble organics from the aqueous waste streams appears to be limited by the small, though significant, solubility of the ionic liquids in the aqueous phase and by difficulty in solvent regeneration.

2.2.8. Demulsifier

In the alkali/surfactant/polymer (ASP), flooding process large quantities of alkali, surfactants, and polymer chemicals are used. During the production process, residual chemicals enter to produce water. Surfactants are mainly responsible for the stability of oil droplets, reducing oil–water interfacial tension, and zeta potential on the surfaces of the oil droplets [78]. The 'skin' surrounding the tiny droplets in the oil–water emulsion prevents the water droplets from uniting and the emulsion remains stable. Demulsifiers are surface-active agents that are effective in disrupting the effects of natural emulsifiers present in the oil. In most crude oils, solids such as iron sulfides, silts, clay, drilling mud, paraffin, etc. complicate the demulsification process [79].

2.3. Biological treatment

Aerobic and anaerobic microorganisms were used in studies of biological treatment of produced water. In aerobic treatment, researchers used activated sludge, trickling filters, sequencing batch reactors (SBRs), chemostate reactors, biological aerated filters (BAF), and lagoons. Four sources of microorganisms were studied in biological treatment:

- Naturally occurring microorganisms,
- Commercial microorganisms,
- Specific groups of microorganisms,
- Acclimated sewage sludge.

Activated sludge is the usual method for treating wastewater. In a continuous-flow pilot plant, an oil skimmer was used to remove oil before treatment in an activated sludge system. Naturally occurring microbial growth was used in an aeration tank. The activated sludge treatment unit could maintain a total petroleum hydrocarbon (TPH) removal efficiency of 98–99% at a solids retention time (SRT) of 20 days [3]. Freire et al. [80] studied COD removal efficiency of acclimated sewage sludge in SBR with different percentages of produced water and sewage. In 45% and 35% (v/v) mixtures of wastewater, COD removal efficiencies varied from 30% to 50%.

On the other hand, in a study to compare total influent organic carbon (TOC) removal efficiency of produced water with acclimated microorganisms in 180 mg/L NaCl, three biological systems including SBR, trickling filters and chemostate reactors were studied as follows:

- 2-L SBR with 24-h cycle (1 h for feed, 20 h for reaction, 2 h for settling, and 1 h for withdrawal).
- A trickling filter equipped with annular plastic supports with packing volume of 1.7 L and hydraulic load of 3 m³/m² h.
- A 1-L chemostate reactor with 8 days hydraulic retention time.

TOC removal efficiency of SBR was higher than that of the trickling filter or of the chemostate but continuous operation of SBR could lead loss of biomass [81].

Freire et al. [80] found that salinity did not have significant effect on COD removal of mixed wastewater, only recalcitrance of organic compounds affected biological treatment; also, Wei et al. [82] showed that when Cl⁻ concentration was increased from 2000 to 36000 mg/L, inhibitory effect of the high salinity on composite microbial culture was negligible. Nevertheless, Dzaf et al. [83] showed that some bacterial consortia degrade crude oil of 80,000 mg/L effectively; however, when salinity increased to 100,000 mg/L, the biodegradation rate fell dramatically because high concentration of sodium chloride causes environmental stress, microbial lysing effects, and promotes loss of biomass [84]. In the aeration tank of salty wastewater treatment plants, slow growth rod-shaped microorganisms dominate the microbial community

[85]. In addition to cell lysing, reduction of filamentous bacteria can affect the integrity of the flocs and raise the turbidity of effluents in biological treatment of salty wastewaters [56]. For improving biological treatment of effluent, membranes can be coupled to it [86].

Palmer et al. [87] used rotating biological surfaces (biodisks) to treat oilfield-produced water. The biodisks were seeded by bacterial sludge from sewage treatment plant microorganisms. BOD and O&G removal efficiency of the plant were 94% and 74%, respectively.

Immobilization of microorganisms can increase treatment efficiency. Li et al. [88] studied *Bacillus* sp. (M-12) immobilized on polyvinyl alcohol (PVA) to remove COD of oilfield-produced water. More than 90% efficiency of COD removal was achieved with initial COD of 2600 mg/L. In another study, Zhao et al. [89] investigated use of B350M and B350 group commercial microorganisms immobilized on poly-ammoniacum carriers. A pair of BAF reactors was studied. Results showed that a hydraulic retention time of 4 h and volumetric load 1.07 kg COD/(m³ day) B350M could remove TOC and oil content of produced water of 78% and 94%, respectively, and of B350, 64% and 86%, respectively.

In biological oxidation, harmless bacteria, algae, fungi, and protozoa convert dissolved organics and ammonia compounds into water and CO₂, nitrates/nitrites, respectively [87], but have no effect on TDS [90]. Beyer et al. [91] studied a two-stage pilot lagoon in series consisting of 80 m³ plastic-lined steel tanks each filled with 60 m³ of fluid. The primary tank was for oxidizing suspended oil and dissolved organic compounds and the second lagoon was designed for oxidizing dissolved ammonia compounds; however, in another study, Palmer et al. [87] used one-stage biological oxidation for removing ammonia and phenols from produced water. Different types of wetland-like free-water surface (FWS) and subsurface flow (SSF) pilot plants were designed, constructed, and tested to treat oilfield-produced water. Results showed that SSF wetland removed more COD than FWS wetland did [90]. Although the wetland is a cost-effective method, the temperature dependence of the system is not a desirable factor. Besides, if these wetlands are not lined, groundwater contamination is not prevented.

The dominant mechanism of hydrocarbon removal by microorganisms in biological treatment is biodegradation and occluding particles by microorganisms similar to bio-flocculation. Activated sludge has the property of adsorbing and occluding not only soluble but also insoluble materials. Bacteria produce surface-active compounds such as surfactants (biosurfactants) and emulsifiers (bioemulsifiers) that enhance the local pseudo-solubility of hydrocarbons and thus improve mass transfer to biodegrading bacteria [92]. Biodegradation of less complex oil components, e.g., normal alkanes is easier than of complex and large molecules. Less biodegradable oil molecules attached to microorganisms will remain in the aeration tank. These components are removed along with sludge in excess-sludge removal processes. The mixture of hydrocarbons and microorganisms are a source of hazardous material which has to be disposed.

When raw wastewater is concentrated, anaerobic degradation of pollutants would be a cost-effective alternative [93]. Gallagher [94] studied biodegradation of organic acids in simulated produced water under anaerobic conditions in the presence of naphthenic acids in a 0.59 L fixed-film bioreactor. Microbial seed used was from the sludge in a produced water holding-pond of the anaerobic digester of a municipal treatment system. Results showed that naphthenic acids were not reduced in anaerobic conditions.

Reed bed technology is using a plant for bioremediation of wastewater. Reed beds can remove hydrocarbons and heavy metals. In a study, an 800-m²-reed bed with *Phragmites australis* plant was used to treat 20 m³/day of produced water; results showed that more than 98% of hydrocarbons were removed [95]. In a similar pilot plant, 3000 m³/day of produced water was treated to reduce total

hydrocarbon concentration by an average of 96%. Metal concentration decreased by 78% for Al, Ba, Cr, Cu, and Zn, up to 40% for Fe, Li, Mn, Pb, As, Cd, Co, Mo, Ni, Se, Tl, and V [96]. Although this system is a cost-effective method, the effluent has to be refined and requires a lot of land.

Table 3 compares different operational conditions and results of biological treatment of produced water.

2.4. Membrane treatment

Different treatments such as chemical and biological methods have been developed to treat wastewater. The following reasons hamper wider application of these methods:

- High cost of treatment,
- Using toxic chemicals,
- Space for installation,
- Secondary pollution.

As a result, physical, membrane-based separation became the promising technology for the 21st century. The membrane pressure-driven process relies on the pore size of the membrane to separate the feed stream components according to their pore sizes [97].

2.4.1. Microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) membranes

Membranes are thin films of synthetic organic or inorganic materials, which selectively separate a fluid from its components. Membrane separation processes such as MF, UF, NF, and RO can be used to separate different sized materials. MF is separation of suspended particles, UF is the separation of macromolecules, and RO is the separation of dissolved and ionic components [98]. NF membranes are generally designed to be selective for multivalent ions rather than for univalent ions. RO membranes are designed to reject all species other than water. They are unable to offer a significant barrier to dissolved gases and certain low-molecular weight organic molecules [99].

Membrane systems can compete with more complex treatment technologies for treating water with high oil content; low mean particle size, and flow rates greater than 150 m³/h and is, consequently, suitable for medium and large offshore platforms [100].

UF is one of the most effective methods for oily wastewater treatment, especially for produced water, in comparison with the traditional separation methods because of its high oil removal efficiency, there is no necessity for chemical additives, energy costs are low, and space requirements small [101]. In a study, Lia et al. [102] studied a tubular UF model equipped with polyvinylidene fluoride membranes modified by inorganic nano-sized aluminum particles to treat oilfield-produced water. Nano-sized alumina particles can improve antifouling performance of membranes. Results of their experiments showed that COD and TOC removal efficiencies of the system were 90% and 98%, respectively, and oil residue was less than 1%.

Bilstad and Espedal [103] compared MF and UF membranes in pilot trial to treat the North Sea oilfield-produced water. Results showed that UF, but not MF, could meet effluent standards for total hydrocarbons, SS, and dissolved constituents. By UF membrane treatment with molecular weight cut-off (MWCO) was between 100,000 and 200,000 Da, total hydrocarbon concentration could be reduced to 2 mg/L from 50 mg/L (96% removal). Benzene, toluene, and xylene (BTX) were reduced by 54%, and some heavy metals like Cu, and Zn were removed to the extent of 95%.

Lee and Frankiewicz [104] tested a hydrophilic UF membrane of 0.01- μ m pore size, in crossflow mode to treat oilfield-produced water. A hydrocyclone was first used to desand and de-oil the

Table 3
Comparison of different biological treatment of produced water.

Produced water	Average characteristics	Pretreatment	Characteristics after pretreatment	Inoculum	Salt content (mg/L)	Process	Volume	Operational condition	Biological treatment	Treatment after biological treatment	Final effluent (mg/L)	Reference
Oilfield	COD = 431 ± 25	Skimming and pre-aeration	–	Naturally occurring	TDS = 34, 110 ± 40	Continuous-flow activated sludge	4530 L	HRT 20 days	Removal COD = 92%	Clarifier, filtration	COD = 14 ± 7	[3]
Oilfield + sewage	COD = 2000	Cotton cloth and filter paper	–	Sewage sludge	TDS = 52100	SBR	2 L	1 day	Removal COD = 50% (35% dilution)	–	–	[80]
Oilfield	COD = 399; TOC = 130	–	–	Acclimated microorganisms	Salinity 220,000	SBR	2 L	0.33 m ³ /m ³ day	Removal TOC = 80%	–	–	[81]
Oilfield	COD = 399; TOC = 130	–	–	Acclimated microorganisms	Salinity 220,000	Trickling filter	1.7 L	0.25 m ³ /m ³ day	Removal TOC = 40%	–	–	[81]
Oilfield	COD = 399; TOC = 130	–	–	Acclimated microorganisms	Salinity 220,000	Chemostate	1 L	–	Removal TOC = 19%	–	–	[81]
Oilfield	COD = 2600	–	–	<i>Bacillus</i> sp. (M-12)	–	Continuous treatment immobilized cells	–	Feeding dilution rate = 0.01 h ⁻¹	Removal COD = 70%	Cinder column	COD = 240	[88]
Oilfield	COD = 125	–	–	Commercial (B350M)	Cl ⁻ = 2780	Biological aerated filter immobilized cells	–	HRT = 4 h	Removal TOC = 19%	–	–	[89]
Oilfield	Removal TOC = 78; oil = 94	–	–	Acclimated natural microorganisms	–	Free-water surface wetland	100 gallon	HRT = 24 h	Effluent TOC = 91 ppm	–	–	[90]
Oilfield	–	–	–	Acclimated natural microorganisms	–	Subsurface flow wetland	100 gallon	HRT = 24 h	Effluent TOC = 38 ppm	–	–	[90]
Oilfield	–	Induced-air floatation	COD = 595 ppm TOC = 115 ppm	–	TDS = 20,000	Aerated lagoon	Two 80 m ³ series	HRT = 7 days	COD = 352 ppm	Sedimentation tank	TSS = 48 ppm	[91]
Oilfield	–	Dissolved gas floatation	TDS = 20 g/L BOD = 180 ppm	Sewage sludge	TDS = 20,000	Rotating biological surface	–	HRT = 2 days A = 72 m ² biologically active surface	TOC = 43 ppm TSS = 493 ppm BOD < 10 ppm O&G = 5 ppm	–	–	[87]
Oilfield	COD = 1600; O&G = 220	MF	O&G = 19 ppm Phenol = 1.9 ppm COD = 960	Sewage sludge	TDS = 80,000	Air-lift reactor	1 L	12–24–48 h	Removal COD 87%	–	–	[138]

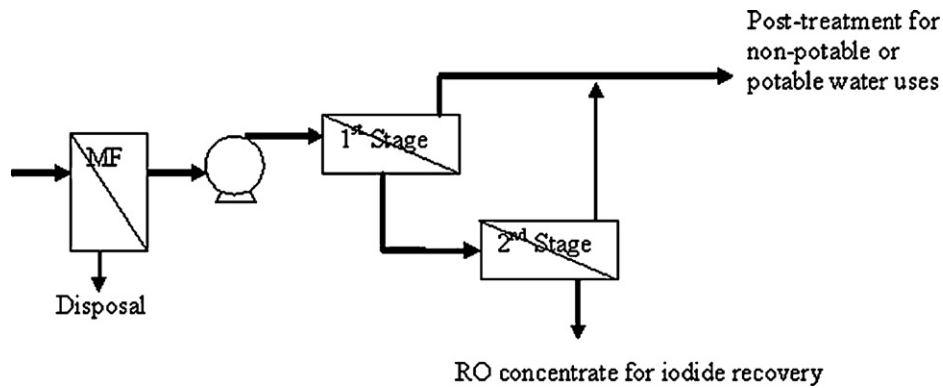


Fig. 5. Proposed MF and two-stage RO or NF membrane treatment. Reprinted with permission from Ref. [109].

wastewater. The hydrocyclone pretreated the raw produced water removing solids and oil content by 73% and 54%, respectively. O&G concentration after UF could be reduced to less than 2 mg/L. The preferred feed-water specification for ideal performance of UF was oil and solids less than 50 and 15 ppm, respectively.

Low-pressure-driven membranes for MF of membrane pore size between 0.1 and 5 μm or UF with membrane pore size less than 0.1 μm or a combination of MF/UF polymeric or ceramic membranes are suitable for removing oil content of oilfield-produced water. However, ceramic membranes are preferred over delicate polymeric membranes because the former have a better tolerance to high temperature, high oil content, foulants, and strong cleaning agents [105]. Ceramic ultra- and NF-membranes are a relatively new class of materials for the treatment of produced water [106].

Chen et al. [107] tested performance of ceramic crossflow MFs to separate oil, grease, and SS from produced water. Permeate quality of dispersed O&G was 5 mg/L and of SS was less than 1 mg/L.

Combined membrane pretreatment and RO technology are effective methods for produced water treatment [108]. Xu et al. [109] investigated a two-stage laboratory-scale membrane to treat gas field produced water generated from sandstone aquifers as shown in Fig. 5.

They studied ultra-low-pressure RO and NF membranes to meet quality standards for potable and irrigation water, and iodide concentration in brine.

2.4.2. Bentonite clay and zeolite membrane

Researches have proposed different materials for construction of membrane in various operational conditions. Key technical obstacles to cost-effective application of membranes in produced water treatment include low average flux rate, flux degradation, and uncertain membrane life. Besides, concerns regarding using membranes in oilfield-produced water treatment include sensitivity to variation in flow and pretreatment and purification [110].

Zeolite membranes possess stable chemical, mechanical, and thermal properties. They can be used in strong solvent environments, and at high temperatures and pressures. RO zeolite membranes are suitable for treating oilfield-produced water to separate different ions (Na^+ , K^+ , Ca^{2+} , and Mg^{2+}) [111]. Li et al. [112] studied desalination of oilfield brine using a pure silicate zeolite

membrane. In this study, they found that ion flux was independent of the operating pressure and it increased as feed concentration was raised from 0.001 to 0.3 M.

A bench-scale cell was used to purify oilfield-produced water with bentonite clay membranes. Results of feeding it with different TDS showed that clay membranes were not suitable for treating produced water with high TDS [113].

2.4.3. Combined systems

In combined systems, different physical, chemical, and biological methods are used for pretreatment of membrane units.

Barrufet et al. [114] proposed adsorption as a physical pretreatment process to precede MF and RO to convert brine to irrigation-quality water. The system included:

- Sorption pellets made of modified clay material,
- MF,
- RO.

Results of a study of the system showed that modified clay could remove oil better than activated carbon and RO could remove more than 95% of TDS.

In a study to treat oilfield-produced waters containing boron and solubilized hydrocarbon compounds, a method comprising water softening to remove substantially all divalent cations combined with RO membrane was used [115]. In a process to meet drinking water quality standards from oilfield-produced water, different physical, and chemical pretreatments for RO were proposed as follows [116]:

- Air floatation,
- Clarification,
- Softening,
- Filtration,
- RO.

Optimized pretreatment and unique separation (OPUS) is a combined physical, and chemical, treatment system which was used for producing boiler feed water. OPUS technology, which consists of multiple treatment processes, including de-gasification, chem-

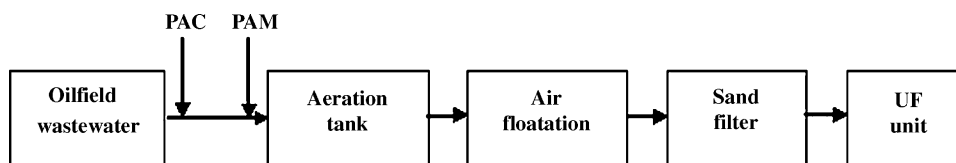


Fig. 6. Process proposed for the treatment of the oilfield wastewater. Reprinted with permission from Ref. [118].

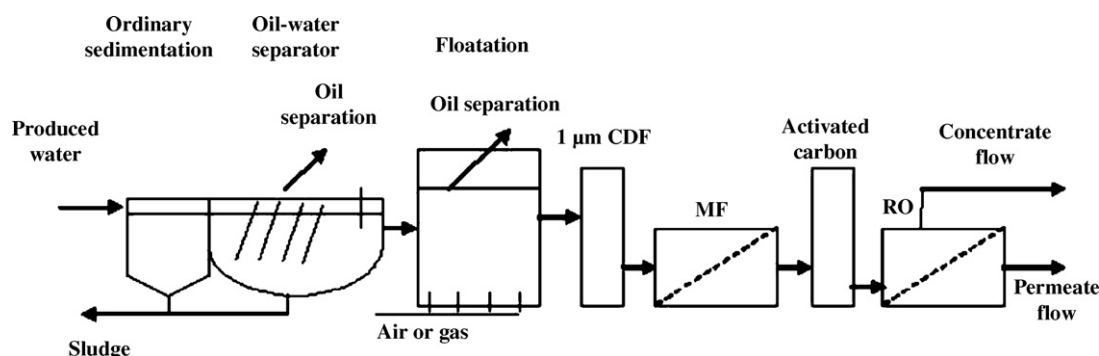


Fig. 7. Proposed treatment alternatives for oil production wastewater. Reprinted with permission from Ref. [119].

ical softening, media filtration, ion-exchange softening, cartridge filtration, was used as a pretreatment for RO. The softened water was used in Chevron's once-through steam generators, which produced this gas–steam—for oil extraction [117]. In a similar method, Qiao et al. [118] proposed a combined system pilot-scale plant to treat oilfield-produced water as shown in Fig. 6. The effluents of the treatment system could reduce oil and SS of oily wastewater to less than 0.5 and 1 mg/L, respectively.

Cakmakce et al. [119] investigated different pretreatment alternatives to RO and NF membrane to find the most appropriate treatment combination. Finally, they proposed a system consisting of the following treatment as shown in Fig. 7. The effluent of the combined system could reduce COD too less than 250 mg/L.

Because of the need for frequent regeneration of physical adsorbers and high running cost and sludge production from chemical treatment, some researchers have proposed biological pretreatment to precede membrane treatment. Nevertheless, the optimal treatment of highly saline wastewater involves a biological treatment of wastewater with acclimated microorganism in saline environment prior to membrane treatment especially with RO [56].

In a pilot study to reuse oilfield-produced water for irrigation and potable water, a series of processes were proposed as shown in Fig. 8. The warm softening process removed 95% hardness (from initial hardness of 1000 mg/L) and RO removed 95% of TDS [120]. On the other hand, Tsang and Martin [121] investigated a different arrangement of a combined system to treat produced water as follows:

- Dissolved gas flotation,
- Walnut shell filtration,
- Warm softening,

- Membrane bioreactor,
- RO.

Doran et al. [122] proposed a pilot process to treat produced water. The process included the following:

- Precipitative softening at pH 9.5–10.0 to remove some hardness and boron, and most of the silica,
- Heat exchange cooling and pH reduction,
- Fixed-film biological oxidation of organics and ammonia removal using a trickling filter,
- Filtration,
- Ion-exchange softening to remove residual hardness,
- RO.

The treated produced water could meet industrial and irrigation requirements.

Kwon et al. [123] concentrated on removing volatile hydrocarbon before biological treatment. They used surfactant-modified zeolite (SMZ) adsorbent beds and a membrane bioreactor (MBR) in combination to reduce the organic carbon content of produced water prior to RO. In the pilot plant, synthetic and real produced water were cycled through SMZ adsorbent units to remove volatile organic compounds (BTEX, acetone) and semivolatile organic compounds (e.g., naphthalene). The effluent from the SMZ units was fed to the MBR for removal of the organic acid component of TOC. In the MBR, acclimated activated sludge was seeded and submerged membranes were used to filter biological treated wastewater. Results of continuous run with the combined system showed that removal efficiency of SMZ was 40% of the influent TOC (600 mg/L). BTEX concentrations were reduced from the initial input level of

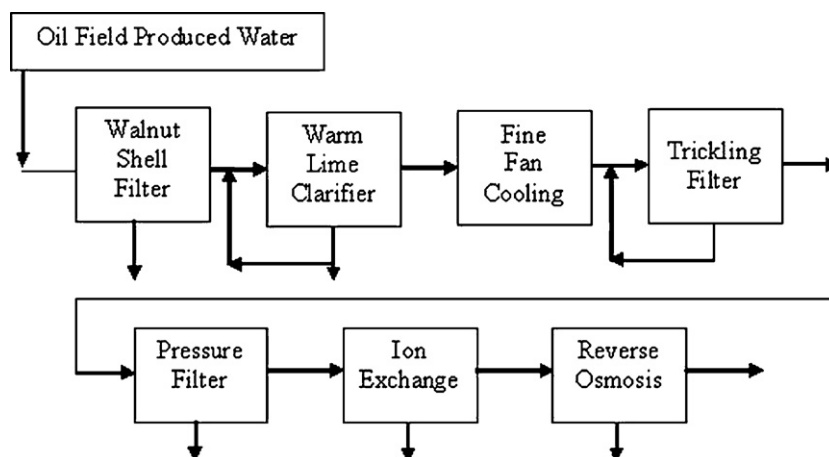


Fig. 8. Pilot plant schematic. Reprinted with permission from Ref. [120].

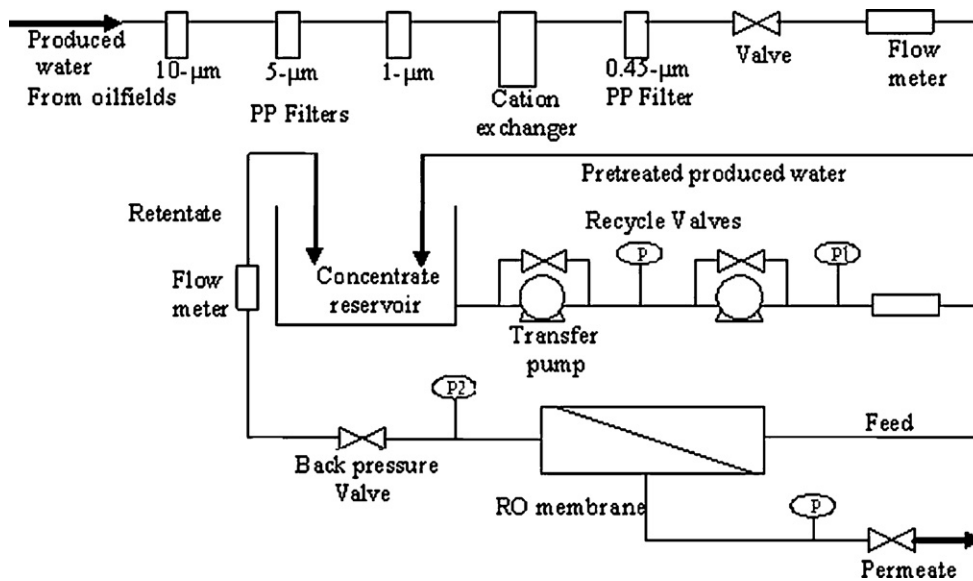


Fig. 9. Flow diagram of pilot-scale reverse osmosis treatment unit. Reprinted with permission from Ref. [124].

70–5 mg/L by the SMZ units and to an average of 2 mg/L after the MBR.

Murray-Gulde et al. [124] proposed a combined onshore system for produced water treatment. They used a hybrid RO-constructed wetland to treat produced water for use in irrigation. The treatment system consisted of different size of filters, a cation exchanger, and RO. The first stage could remove 95% and 94% of conductivity and TDS, respectively (Fig. 9). The RO permeate flow to a pilot-scale constructed wetland. The wetland consisted of four cells in series with vegetation collected from the oilfield site.

Although RO can produce low concentration permeates, it requires chemical, and/or biological pretreatment. High initial cost of membranes, chemical cleaning after fouling, generation of chemical cleaner waste, and producing concentrates as a new source of waste that should be discharged or further treated, are common problems of oil and gas industries operators.

2.4.4. Modified membrane systems to reduce fouling

Fouling is adsorption or accumulation of certain components of produced water on the membrane surface or in the membrane pores that eventually causes flux efficiency to decline. Fouling is a fundamental limitation to economic viability of membrane in produced water treatment [125].

New Logic Inc. [126] used a vibration shear enhanced process (VSEP) system that employed torsional vibration of the membrane surface. The system created very high shearing energy at the surface and the pores. The result was a reduction of colloidal fouling and

polarization of membrane due to concentration of rejected materials. Fig. 10 shows comparison of crossflow and VSEP separation processes. Table 4 shows effluent characteristics of produced water by VSEP.

On the other hand, EXTRAN super (TM) which is composed of natural cellulose is resistant to all hydrocarbons and organic solvents and is not fouled by oil molecules and calcium scaling. In membranes that were formulated with this chemical, water passed through the membrane surface by the diffusion process, while hydrophobic hydrocarbons were rejected [127].

Table 5 summarizes different operational conditions and results for produced water treatment with membranes.

Table 4
Effluent characteristics of produced water by VSEP [126].

Typical VSEP	Untreated (mg/L)	NF Filtrate (mg/L)	RO Filtrate (mg/L)
TOC	810	120	20
TSS	9000	ND	ND
COD	2600	270	71
O&G	580	16	ND
Chloride	4700	2900	15
Sulfate	210	ND	ND
Calcium	400	8	ND
Magnesium	50	ND	ND
Zinc	100	5	ND

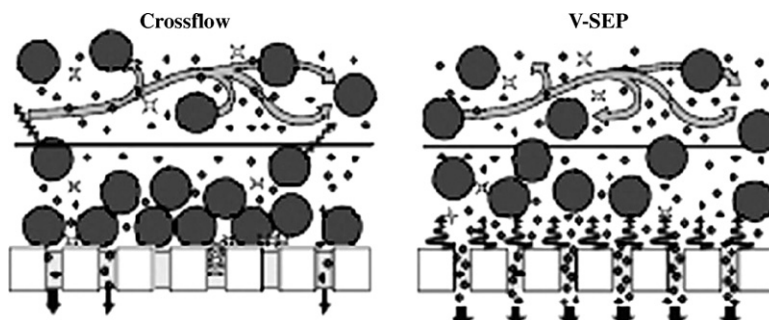


Fig. 10. Comparison of crossflow and VSEP separation. Reprinted with permission from Ref. [126].

Table 5
Membrane treatment of produced water.

Produced water	Initial characteristics	Pretreatment	Characteristics after pretreatment	Membrane type	Surface (m ²)	Pressure	Flux (L/m ² h)	Pore size	Flow velocity (m/s)	Effluent characteristics	Reference
Oilfield	–	Sedimentation, coagulation sand filtration	COD = 637; O&G = 15.5; TOC = 214.9; SS = 15.8	Tubular UF module equipped with polyvinylidene fluoride membranes modified by inorganic nano-sized alumina	0.01256	0.1 MPa = 1 bar	170	MWCO = 35 kDa	7.8	COD removal = 90%; TOC removal = 98%; O&G < 1 mg/L; SS < 1 mg/L	[102]
Oilfield	–	Hydrocyclone	Total HC = 50 ppm; BTX = 2.6 ppm; Cu = 9.1 ppm; Zn = 2.8	Tubular PVDF-UF	0.9	6–10 bar	309–598	MWCO = 100 kDa	1.4–4	Total HC removal = 95%; BTX removal = 54%; Cu removal = 96; Zn removal = 96	[103]
Oilfield	TSS = 6.1–158 ppm; O&G = 100–1000 ppm	De-oiling hydrocyclone; desanding hydrocyclone; membrane prefilter	TSS = 3–27.6 ppm; O&G = 80	UF + .45 µm cartridge filter	15.8	50 psi = 3.4 bar	17	0.1 µm	–	Dispersed oil removal > 90%; NO dissolved HC removal O&G < 2 ppm	[104]
Oilfield	–	–	–	Ceramic crossflow MF	0.2025	–	–	0.2–0.5 µm	0.9–4.5	O&G < 5 ppm; TSS < 1 ppm	[107]
Gas field	–	MF-hollow fiber membranes	TDS = 5,520 ± 718 mg/L; O&G = 0.70 ± 0.41 mg/L	NF-thin-film composite polyamide RO-thin-film composite polyamide	–	–	27	–	–	–	[109]
Oilfield	–	Dissolved air flotation	COD = 985 ppm; O&G = 230	Cellulose acetate hollow fiber membrane	–	1 bar	119	MWCO = 130 kDa	0.8	COD = 23 mg/L; O&G = 4 mg/L	[101]
Synthetic-produced water	250 and 1000 ppm crude oil	–	–	a-Alumina ceramic membranes	45.3 cm ²	10 and 20 psi	15–66	0.2 and 0.8 µm	0.24 and 0.91	Oil removal 99.3–99.9%	[137]
Synthetic-produced water	250 and 1000 ppm crude oil	–	–	Surface-modified polyacrylonitrile (PAN) membrane	185 cm ²	10 and 20 psi	5–37	0.1 µm	0.24 and 0.91	Oil removal 99.3–99.9%	
Oilfield	SS = 30–150 ppm; O&G = 50–200 ppm; COD = 400–500 mg/L	Chemical treatment + aeration + sand filter	SS = 4–8 mg/L; O&G < 1.5 mg/L; COD = 111	PVC alloy hollow fiber	40 m ²	–	–	5–7 nm	–	SS = < 0.6 mg/L; O&G < 0.5 mg/L; COD = 73	[118]

PVDF: polyvinylidene fluoride.

3. Performance evaluation and analysis of treatment technology

Authors of [33] proposed a sequence to assess the effectiveness and performance of the various treatment methods and technologies. It is a five-step ranking as follows:

- Step 1: ability to remove technology specific contaminants.
- Step 2: consumption of resources to achieve desired removal using given technologies.
- Step 3: requirement of pre- or post-treatment technologies with given technologies.
- Step 4: durability of the treatment technology.
- Step 5: mobility of the treatment units.

The ranking of each step depends on the ranking of the other steps and the quality of effluent is affected by the evaluation in separate step:

- Step 6: level of contaminants in influent produced water.

After estimating the ranking of each of the five steps, the overall rank is calculated on the basis the following formula:

$$\text{overall rank} = \frac{\text{step 1} + \text{step 2} + \text{step 3} + \text{step 4} + \text{step 5}}{\text{step 6}}$$

The highest and lowest overall ranking is 7 and 1, respectively. At the ranking of 7 the treatment method has better performance, flexibility, and economics than the rankings below it.

The Gas Research Institute (GRI) proposed a program to assess technology of environmental control strategies in the natural gas production industry [128]. It developed a database and a management information system, or model, to assist gas producer companies in choosing the optimal produced water management strategy. Using this information, gas producer companies can assess the management strategies.

Arthur et al. [33] compared advantages and disadvantages of current produced water treatment technologies (Table 6).

4. Produced water treatment cost evaluation

OSPAR [129] proposed a method for evaluating produced water treatment cost. The method was based on three model situations:

1. Small gas installation (based on 26 gas installations with small produced water discharges).
2. Large gas installations (based on 27 gas installations with larger produced water discharges).
3. Oil installations (based on 7 oil installations).

Capital expenses (CAPEX) and operational expenses (OPEX) were estimated based on market conformity (price level 2000). Estimates were based on price indications from suppliers, designers, and fitters. For CAPEX, investment was estimated for each technique based on the following costs:

- Design and project management,
- Equipment,
- Transport,
- Fitting,
- Unforeseen expenses.

For OPEX, all costs were based on the price level prevailing in the reference year 2000. Points of departure for calculation of yearly operational costs are presented in Table 7.

Jackson and Myers [90] provided cost estimates for produced water disposal methods. Disposal costs are dependent upon the volume and chemistry of produced water as also size and location

of the operation. Table 8 shows produced water disposal methods and costs.

5. Discussion and future developments

Co-produced water is the most significant waste stream for oil and gas producer countries. For each barrel of oil produced, 3–10 barrels of produced water are generated. About 95% of the water can be reinjected after pretreatment for enhancing oil recovery; the fraction remaining is still considerable [130]. On the other hand, in gas fields water injection is not applied. Consequently, today using cost-effective and efficient treatment technology for treating produced water to reduce contaminants for discharge and/or reuse constitutes a challenge for oil and gas companies. Because produced water characteristics vary from gas fields to oil fields and from one well to another and on the age of the well, a unique technique cannot be recommended for achieving all environmental standards, recycling, and reuse requirements. The various methods presented in previous sections offer some advantages and disadvantages. They are: (1) the general disadvantages associated with physical methods are high initial capital costs and sensitivity to variable water input, (2) for chemical treatment, hazardous sludge generation with subsequent treatment and disposal problems, high running costs, and sensitivity to initial concentration of wastewater, and (3) for biological treatment, sensitivity to variation of organic chemicals as well as salt concentration of influent waste. These factors limit suggestions for a general recommendation for treating produced water.

For treating produced water, the suitable strategy depends on the following major criteria.

5.1. Source of produced water and concentration of pollutants

In offshore facilities, lack of space encourages designers to use physically and chemically compact methods. In onshore processes, biological treatment with physico-chemical pretreatment is preferred. Where the concentrations of dissolved and hazardous inorganic- and organic-components are high it is essential to use combined physico-chemical (in offshore) and/or biological methods (in onshore) methods before discharge.

5.2. Final requirements for discharge, recycle or reuse

Year after year, impacts of produced water discharge on environment have forced authorities to implement progressively more stringent standards for discharging treated wastewater as well as for its reinjection to aquifers. Even by combining physico-chemical and biological treatment, not all hazardous pollutants can be removed. Newly developed technologies like membranes can help to refine final effluent to meet all requirements [67].

In offshore facilities, cost-effective and high efficiency demulsifiers, effective physical oil/water separators, and high efficiency adsorbers with effective regeneration processes are preferred techniques.

In addition, a promising technology is membranes with low fouling characteristics especially for offshore units; also, well-designed hydrodynamics techniques such as vibration shear-enhanced processes reduce fouling, enhance flux rates, and minimize usage of cleaning chemicals.

In onshore production sites, where enough space is available, using high efficient halophile oil degrading microorganisms in biological treatment is a cheap, effective and environmental friendly method. Membrane-coupled SBR biological treatment systems prevent organic shocks and retain slow growth microorganisms in aeration tank [131]. Combined physical-biological-UF-RO processes are effective methods for onshore facilities. Anaerobic

Table 6
Comparison of current technologies for oil and gas produced water treatment [33].

Treatment	Description	Advantages	Disadvantages	Waste stream	Oil and gas produced water applications
Corrugated plate separator	Separation of free oil from water under gravity effects enhanced by flocculation on the surface of corrugated plates	No energy required, cheaper, effective for bulk oil removal and suspended solid removal, with no moving parts, this technology is robust and resistant to breakdowns in the field	Inefficient for fine oil particles, requirement of high retention time, maintenance	Suspended particles slurry at the bottom of the separator	Oil recovery from emulsions or water with high oil content prior to discharge. Produced water from water-driven reservoirs and water flood production are most likely feed stocks. Water may contain oil and grease in excess of 1000 mg/L.
Centrifuge	Separation of free oil from water under centrifugal force generated by spinning the centrifuge cylinder	Efficient removal of smaller oil particles and suspended solids, lesser retention time high-throughput	Energy requirement for spinning, high maintenance cost	Suspended particles slurry as pretreatment waste	
Hydroclone	Free oil separation under centrifugal force generated by pressurized tangential input of influent stream	Compact modules, higher efficiency and throughput for smaller oil particles	Energy requirement to pressurize inlet, no solid separation, fouling, higher maintenance cost		
Gas floatation	Oil particles attach to induced gas bubbles and float to the surface	No moving parts, higher efficiency due to coalescence, easy operation, robust and durable	Generation of large amount of air, retention time for separation, skim volume	Skim off volume, lumps of oil	
Extraction	Removal of free or dissolved oil soluble in lighter hydrocarbon solvent	No energy required, easy operation, removes dissolved oil	Use of solvent, extract handling, regeneration of solvent	Solvent regeneration waste	Oil removal from water with low oil and grease content (<1000 mg/L) or removal of trace quantities of oil and grease prior to membrane processing. Oil reservoirs and thermogenic natural gas reservoirs usually contain trace amounts of liquid hydrocarbons.
Ozone	Strong oxidizers oxidize soluble contaminant and easy operation, efficient for primary treatment of soluble constituents remove them as precipitate	Easy operation, efficient for primary treatment of soluble constituents	On-site supply of oxidizer, separation of precipitate, byproduct CO ₂ , etc.	Solids precipitated in slurry form	
Adsorption	Porous media adsorbs contaminants from the influent stream	Compact packed bed modules, cheaper, efficient	High retention time, less efficient at higher feed concentration	Used adsorbent media, regeneration waste	
Lime softening	Addition of lime to remove carbonate, bicarbonate, etc. hardness	Cheaper, accessible, can be modified	Chemical addition, post-treatment necessary	Used chemical and precipitated waste	These technologies typically require less power and less pretreatment than membrane technologies. Suitable produced waters will have TDS values between 10,000 and 1000 mg/L. Some of the treatments remove oil and grease contaminants and some of them require oil and grease contaminants to be treated before these operations.
Ion-exchange	Dissolved salts or minerals are ionized and removed by exchanging ions with ion-exchangers	Low energy required, possible continuous regeneration of resin, efficient, mobile treatment possible	Pre- and post-treatment require for high efficiency, produce effluent concentrate	Regeneration chemicals	
Rapid spray evaporation	Injecting water at high velocity in heated air evaporates the water which can be condensed to obtained treated water	High quality treated water, higher conversion efficiency	High energy required for heating air, required handling of solids	Waste in sludge form at the end of evaporation	
Freeze–thaw evaporation	Utilize natural temperature cycles to freeze water into crystals from contaminated water and thaw crystals to produce pure water	No energy required, natural process, cheaper	Lower conversion efficiency, long operation cycle	–	
Microfiltration	Membrane removes micro-particles from the water under the applied pressure	Higher recovery of fresh water, compact modules	High energy required, less efficiency for divalent, monovalent salts, viruses, etc.	Concentrated waste from membrane backwash during membrane cleaning, concentrate stream from the filtration operation	Removal of trace oil and grease, microbial, soluble organics, divalent salts, acids, and trace solids. Contaminants can be targeted by the selection of the membrane.
Ultrafiltration	Membrane removes ultraparticles from the water under the applied pressure	Higher recovery of fresh water, compact modules, viruses and organics, etc. removal	High energy, membrane fouling, low MW organics, salts, etc		
Reverse osmosis	Pure water is squeezed from contaminated water under pressure differential	Removes monovalent salts, dissolved contaminants, etc., compact modules	High pressure requirements, even trace amounts of oil and grease can cause membrane fouling		Removal of sodium chloride, other monovalent salts, and other organics. Some organic species may require pretreatment. While energy costs increase with higher TDS, RO is able to efficiently remove salts in excess of 10,000 mg/L.
Activated sludge	Using oil degrading microorganisms to degrade contaminants within water	Cheaper, simple and clean technology	Oxygen requirement, large dimensions of the filter	Sludge waste at the end of the treatment	Removal of suspended and trace solids, ammonia, boron, metals, etc. Post-treatment is normally required to separate biomass, precipitated solids, dissolved gases, etc.
Constructed wetland treatment	Natural oxidation and decomposition of contaminants by flora and fauna	Cheaper, efficient removal of dissolved and suspended contaminants	Retention time requirement, maintenance, temperature and pH effects		

Table 7
Points of departure for calculation of yearly operational costs [129].

	New offshore installation	Existing offshore installation
Depreciation	$0.163 \times I$	$0.264 \times I$
Maintenance	$\text{€}/\text{m}^3$ (i.s./e.f.) $\times Q$	$\text{€}/\text{m}^3$ (i.s./e.f.) $\times Q$
Spare parts	$\text{€}/\text{m}^3$ (i.s./e.f.) $\times Q$	$\text{€}/\text{m}^3$ (i.s./e.f.) $\times Q$
Use of chemicals	$\text{€}/\text{kg} \times \text{kg}/\text{m}^3$ (i.s.) $\times Q$	$\text{€}/\text{kg} \times \text{kg}/\text{m}^3$ (i.s.) $\times Q$
Use of potable water	$\text{€}3.40/\text{m}^3 \times \text{amount m}^3/\text{year}$ (i.s.)	$\text{€}3.40/\text{m}^3 \times \text{amount m}^3/\text{year}$ (i.s.)
Other regular uses	i.s.	i.s.
Operation (crew)	$\text{€}32.00/\text{h} \times \text{amount h}/\text{year}$ (e.f.)	$\text{€}32.00/\text{h} \times \text{amount h}/\text{year}$ (e.f.)
Energy	$\text{€}0.14/\text{kWh} \times \text{kWh}/\text{year}$ (i.s.)	$\text{€}0.14/\text{kWh} \times \text{kWh}/\text{year}$ (i.s.)
Removal of sludge		
Regular quantity	$\text{€}36,500/\text{t} \times \text{t}/1000 \text{ kg} \times \text{amount kg sludge}/\text{m}^3$ (e.f.) $\times Q$	$\text{€}36,500/\text{t} \times \text{t}/1000 \text{ kg} \times \text{amount kg}/\text{m}^3$ (e.f.) $\times Q$
Small quantity (<3500 kg/year)	$\text{€}68,000/\text{t} \times \text{t}/1000 \text{ kg} \times \text{amount kg}/\text{m}^3$ (e.f.) $\times Q$;	$\text{€}68,000/\text{t} \times \text{t}/1000 \text{ kg} \times \text{amount kg}/\text{m}^3$ (e.f.) $\times Q$
Mercury containing sludge	$\text{€}114,000/\text{t} \times \text{t}/1000 \text{ kg} \times \text{amount kg}/\text{m}^3$ (e.f.) $\times Q$	$\text{€}114,000/\text{t} \times \text{t}/1000 \text{ kg} \times \text{amount kg}/\text{m}^3$ (e.f.) $\times Q$
Radioactive waste	$\text{€}1,500,000/\text{t} \times \text{t}/1000 \text{ kg} \times \text{amount kg}/\text{m}^3$ (e.f.) $\times Q$	$\text{€}1,500,000/\text{t} \times \text{t}/1000 \text{ kg} \times \text{amount kg}/\text{m}^3$ (e.f.) $\times Q$

I, total investment costs in Euro (CAPEX); *Q*, yearly treatment flow in m³/year; i.s., information supplier; e.f., best estimate by authors fact sheet. Usually, yearly OPEX will amount approximately 35–45% of the CAPEX (*I*).

Table 8
Produced water disposal methods and costs [90].

Method	Estimated cost (\$/bbl)	Limitation	Benefits
Surface discharge	0.01–0.08	Energy costs	Livestock, wildlife, irrigation
Secondary recovery	0.05–1.25	Infrastructure	Increase production
Shallow reinjection	0.10–1.33	Energy and maintenance	Recharge aquifer
Evaporation pits	0.01–0.80	Sequestering from wildlife/soil contamination	Livestock impoundment
Commercial water hauling	0.01–5.50	Distance	–
Disposal wells	0.05–2.65	–	–
Freeze–thaw evaporation	2.65–5.00	Regional climate	Water/salt separation
Evaporation pits + flowlines	1.00–1.75	–	–
Constructed wetland	0.001–2.00	Land area	Livestock, wildlife habitat, communities, education
Electrodialysis	0.02–0.64	CAPEX	
Induced air flotation for de-oiling	0.05	CAPEX	
Anoxic/aerobic granular activated carbon	0.083	CAPEX	

treatment (as a cheap alternative) to high organic concentrations of produced water has not been considered as much as aerobic treatment. Using cheap and efficient immobilization materials in biological treatment for increasing biological treatment efficiency is recommended for future research.

6. Conclusions

This review article examined the sources, characteristics, and extent of pollution created by oil and gas produced water and the different methods available for its treatment and disposal. In produced water treatment, no single technology can meet suitable effluent characteristics, thus two or more treatment systems might be used in series operation. Choice of the best technology is based on produced water chemistry, cost-effectiveness, space availability, reuse and discharge plans, durable operation, and byproducts. Although raw produced water is toxic, by using suitable technology it can be treated for different reuse—even as drinking water—especially for water-stressed countries.

References

- J.M. Neff, Bioaccumulation in Marine Organisms: Effect of Contaminants from Oil Well Produced Water, Elsevier, The Netherlands, 2002.
- USEPA, <http://www.epa.gov>.
- G.T. Tellez, N. Nirmalakhandan, J.L. Gardea-Torresdey, Performance evaluation of an activated sludge system for removing petroleum hydrocarbons from oilfield produced water, *Adv. Environ. Res.* 6 (2002) 455–470.
- OSPAR Commission, Report on Discharges Spills and Emissions from Offshore Oil and Gas Installations, http://www.ospar.org/documents/dbase/publications/p00221_Offshore%20report%202003.pdf, 2005.
- J. Veil, M.G. Puder, D. Elcock, R.J.J. Redweik, A White Paper Describing Produced Water from Production of Crude Oil, Natural Gas and Coal Bed Methane, http://www.netl.doe.gov/publications/oil_pubs/prodwaterpaper.pdf, 2004.
- P. Ekins, R. Vanner, J. Firebrace, Zero emissions of oil in water from offshore oil and gas installations: economic and environmental implications, *J. Clean. Prod.* 15 (2007) 1302–1315.
- B. Dal Ferro, M. Smith, Global Onshore and Offshore Water Production, <http://www.touchoilandgas.com/global-onshore-offshore-water-a7137-1.html>, 2007.
- Z. Khatib, P. Verbeek, Water to value—produced water management for sustainable field development of mature and green fields, in: SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production, Kuala Lumpur, Malaysia, 20–22 March, 2002.
- R.R. Reynolds, R.D. Kiker, Produced Water and Associated Issues. A Manual for the Independent Operator, <http://www.pttc.org/pwm/produced.water.pdf>, 2003.
- J.P. Fillo, S.M. Koraido, J.M. Evans, Sources, characteristics, and management of produced waters from natural gas production and storage operations, in: J.P. Ray, F.R. Engelhardt (Eds.), *Produced Water: Technological/Environmental Issues and Solutions*, Plenum Publishing Corp., New York, 1992, pp. 151–162.
- B.R. Hansen, S.H. Davies, Review of potential technologies for the removal of dissolved components from produced water, *Chem. Eng. Res. Des.* 72 (1994) 176–188.
- D.T. Bostick, H. Luo, H. Hindmarsh, Characterization of Soluble in Produced Water, Oak Ridge National Laboratory, 2002, <http://www.ornl.gov/~webworks/cppr/y2002/rpt/112478.pdf>.
- M.T. Stephenson, A survey of produced water studies, in: J.P. Ray, F.R. Engelhardt (Eds.), *Produced Water: Technological/Environmental Issues and Solutions*, Plenum Publishing Corp., New York, 1992, pp. 1–12.
- T.I.R. Utvik, Chemical characterization of produced water from four offshore oil production platforms in the North Sea, *Chemosphere* 39 (1999) 2593–2606.
- L.B. Li, S. Yan, X.D. Zeng, D.Q. Lin, Analysis of organic compounds in oilfield produced water, *Petrochem. Technol.* 31 (2002) 472–475.
- L.G. Faksness, P.G. Grini, P.S. Daling, Partitioning of semi-soluble organic compounds between the water phase and oil droplets in produced water, *Mar. Pollut. Bull.* 48 (2004) 731–742.
- R.P.M.W. Jacobs, R.O.H. Grant, J. Kwant, J.M. Marquenie, E. Mentzer, The composition of produced water from Shell operated oil and gas production in the North Sea, in: J.P. Ray, F.R. Engelhardt (Eds.), *Produced Water: Technological/Environmental Issues and Solutions*, Plenum Publishing Corp., New York, 1992, pp. 13–22.

- [18] R.L. Pitre, Produced water discharges into marine ecosystems, in: Annual Off-shore Technology Conference, Houston, USA, 7 May, 1984.
- [19] T.I.R. Utvik, Composition, Characteristics of produced water in the North Sea, in: Produced Water Workshop, Aberdeen, Scotland, 26–27 March, 2003.
- [20] S.F.J. Vegueria, J.M. Godoy, N. Miekeley, Environmental impact studies of barium and radium discharges by produced waters from the “Bacia de Campos” oil-field offshore platforms, Brazil, *J. Environ. Radioact.* 62 (2002) 29–38.
- [21] T. Gåfvert, I. Færevik, A.L. Rudjord, Assessment of the discharge of NORM to the North Sea from produced water by the Norwegian oil and gas industry, *Radioact. Environ.* 8 (2006) 193–205.
- [22] P. McCormack, P. Jones, M.J. Hetheridge, S.J. Rowland, Analysis of oilfield produced waters and production chemicals by electrospray ionisation multi-stage mass spectrometry (ESI-MSn), *Water Res.* 35 (2001) 3567–3578.
- [23] W. Weidong, L. Ximing, C. Yong, Z. Songting, J. Yan, The technology of microbial treating drained water of oil field, in: SPE Asia Pacific Improved Oil Recovery Conference, Kuala Lumpur, Malaysia, 8–9 October, 2001.
- [24] D. Shubo, Y. Gang, C. Zhongxi, W. Di, X. Fujun, J. Neng, Characterization of suspended solids in produced water in Daqing oilfield, *Colloids Surf. A* 332 (2009) 63–69.
- [25] J.M. Neff, T.C. Sauer, N. Maciolek, Composition, fate and effects of produced water discharges to nearshore marine waters, in: J.P. Ray, F.R. Engelhardt (Eds.), Produced Water: Technological/Environmental Issues and Solutions, Plenum Publishing Corp., New York, 1992, pp. 371–386.
- [26] J.K. Otton, Environmental Aspects of Produced-water Salt Releases in Onshore and Coastal Petroleum-producing Areas of the Conterminous, <http://www.worldcat.org/oclc/72671289>, 2006.
- [27] N. Elias-Samllalingsh, J.B.R. Agard, Application of toxicity identification evaluation procedures for characterizing produced water using the tropical *mysid*, *metamysidopsis insularis*, *Environ. Toxicol. Chem.* 23 (2003) 1194–1203.
- [28] C.C. Karman, H.G. Reerink, Dynamic assessment of the ecological risk of the discharge of produced water from oil and gas producing platforms, *J. Hazard. Mater.* 61 (1998) 43–51.
- [29] S.B. Henderson, S.J.W. Grigson, P. Johnson, B.D. Roddie, Potential Impact of production chemicals on the toxicity of produced water discharges from North Sea oil platforms, *Mar. Pollut. Bull.* 38 (1999) 1141–1151.
- [30] S.J.W. Grigson, A. Wilkinson, P. Johnson, C.F. Moffat, A.D. McIntosh, Measurement of oilfield chemical residues in produced water discharges and marine sediments, *Rapid Commun. Mass Spectrom.* 14 (2000) 2210–2219.
- [31] L.D. Hamilton, A.F. Meinhold, g. Nagy, Health risk assessment for radium discharged in produced waters, in: J.P. Ray, F.R. Engelhardt (Eds.), Produced Water: Technological/Environmental Issues and Solutions, Plenum Publishing Corp., New York, 1992, pp. 303–315.
- [32] J.V. Veil, Research to Improve Water-use Efficiency and Conservation: Technologies and Practice, http://www.ead.anl.gov/pub/doc/testimony_veil_final.pdf, 2007.
- [33] J.D. Arthur, B.G. Langhus, C. Patel, Technical Summary of Oil and Gas Produced Water Treatment Technologies, http://www.rrc.state.tx.us/commissioners/williams/environment/produced_water.trtmnt.Tech.pdf, 2005.
- [34] D.B. Boysen, J.E. Boysen, J.A. Boysen, Creative Strategies for Produced Water Disposal in the Rocky Mountain Region, <http://www.ipec.utulsa.edu/Conf2002/boysen.89.pdf>, 2002.
- [35] F.T. Tao, R.D. Hobbs, J.L. Sides, J.D. Wieser, C.A. Dyke, D. Tuohey, P.F. Pliker, Conversion of oilfield produced water into an irrigation/drinking quality water, in: SPE/EPA Exploration and Production Environmental Conference, San Antonio, USA, 3–7 October, 1993.
- [36] D.H. Doyle, A.B. Brown, Produced Water treatment and hydrocarbon removal with organoclay, in: SPE Annual Technical Conference and Exhibition, Dallas, Texas, USA, 1–4 October, 2000.
- [37] M.S. Carvalho, M.D. Clarisse, E.F. Lucas, C.C.R. Barbosa, Evaluation of the polymeric materials (DVB copolymers) for produced water treatment, in: SPE International Petroleum Exhibition and Conference, Abu Dhabi, UAE, 13–16 October, 2002.
- [38] C. Mitchell, Means, M.L. Braden, Process for removing water-soluble organic compounds from produced water, US Patent No. 5,135,656 (1992).
- [39] T.J. McGhee, Treatment of Brackish and Saline Waters, Water Supply and Sewerage, 6th ed., McGraw-Hill Inc., New York, 1991.
- [40] J.S. Janks, F. Cadena, Investigations into the use of modified zeolites for removing benzenes, toluene and xylene from saline produced water, in: J.P. Ray, F.R. Engelhardt (Eds.), Produced Water: Technological/Environmental Issues and Solutions, Plenum Publishing Corp., New York, 1992, pp. 473–488.
- [41] Y. Yang, X. Zhang, Z. Wang, Oilfield produced water treatment with surface-modified fiber ball media filtration, *Water Sci. Technol.* 46 (2002) 165–170.
- [42] S.A. Ali, L.R. Henry, J.W. Darlington, J. Occipinti, New filtration process cuts contaminants from offshore produced water, *Oil Gas J.* 96 (1998) 73–78.
- [43] S.M. Liu, Z.J. Zhang, M.H. Jiang, Treatment of ASP produced water with hydrophilic fibre ball filtration, *J. Harbin Inst. Technol.* 6 (2007) 837–841.
- [44] R.J. Jan, T.G. Reed Jr., New caustic process for softening produced water for steam generation, *Prod. Eng.* 7 (1992) 199–202.
- [45] D.H. Doyle, F. Daniel, A.B. Brown, Field test of produced water treatment with polymer modified bentonite, in: SPE Rocky Mountain Regional meeting held in Casper, Wyoming, USA, 18–21 May, 1997.
- [46] M.J. Plebon, M. Saad, S. Fraser, Further Advances in Produced Water De-oiling Utilizing a Technology that Removes and Recovers Dispersed Oil in Produced Water 2 micron and Larger, <http://www.ipec.utulsa.edu/Conf2005/Papers/Plebon.Further.Advances.pdf>, 2005.
- [47] F. Li, X. Wu, J. Wu, X. Xu, S. Ma, Kinetic study of adsorption of oil from oilfield produced water using modified porous ceramics filtration media in column mode, in: Bioinformatics and Biomedical Engineering, ICBBE, The 2nd International Conference, Shanghai, China, 16–18 May, 2008.
- [48] M.A. Adewumi, J.E. Erb, R.W. Watson, Design considerations for a cost effective treatment of stripper oil well produced water, in: J.P. Ray, F.R. Engelhardt (Eds.), Produced Water: Technological/Environmental Issues and Solutions, Plenum Publishing Corp., New York, 1992, pp. 511–523.
- [49] B.L. Knudsen, M. Hjelsvold, T.K. Frost, P.G. Grini, C.F. Willumsen, H. Torvik, Meeting the zero discharge challenge for produced water, in: Proceeding of the Seventh SPE International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production, Calgary, Alberta, Canada, 29–31 March, 2004.
- [50] J.J. Seureau, Y. Aurelle, M.E. Hoyack, A three-phase separator for the removal of oil and solids from produced water, in: SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA, 25–28 September, 1994.
- [51] S. Liu, X. Zhao, X. Dong, B. Miao, W. Du, Treatment of produced water from polymer flooding process using a new type of air sparged hydrocyclone, in: SPE Asia Pacific Health, Safety and Environment Conference and Exhibition, Kuala Lumpur, Malaysia, 19–21 September, 2005.
- [52] S. Deng, R. Bai, J.P. Chen, Z. Jiang, G. Yu, F. Zhou, Z. Chen, Produced water from polymer flooding process in crude oil extraction: characterization and treatment by a novel crossflow oil–water separator, *Sep. Purif. Technol.* 29 (2002) 207–216.
- [53] W.M.G.T. Van den Broek, M.J. Van der Zande, Comparison of plate separator, centrifuge and hydrocyclone, in: SPE International Oil and Gas Conference and Exhibition, Beijing, China, 2–6 November, 1998.
- [54] T.A. Bertness, S.P. Lipoma, Method of treating saline water, US Patent No. 4,877,536 (1989).
- [55] W. Heins, D. Peterson, Use of evaporation for heavy oil produced water treatment, *J. Can. Petrol. Technol.* 44 (2005) 26–30.
- [56] O. Lefebvre, R. Moletta, Treatment of organic pollution in industrial saline wastewater: a literature review, *Water Res.* 40 (2006) 3671–3682.
- [57] R.F. Bob Becker, Produced and Process Water Recycling Using Two Highly Efficient Systems to Make Distilled Water, in: SPE Annual Technical Conference and Exhibition, Dallas, Texas, USA, October 1–4, 2000.
- [58] G.J. Thoma, M.L. Bowen, D. Hollensworth, Dissolved air precipitation solvent sublation for oilfield produced water treatment, *Sep. Purif. Technol.* 16 (1999) 101–107.
- [59] K. Lang, Managing Produced Water, <http://www.pttc.org/technology-summaries/statev6no4.htm>, 2000.
- [60] J.A. Sorensen, J. Boysen, D. Boysen, T. Larson, Field Application of the Freeze/Thaw Evaporation (FTE®) Process for the Treatment of Natural Gas Produced Water in Wyoming, <http://www.osti.gov/servlets/purl/791058-6iLoKQ/native>, 2002.
- [61] L. Dallbauman, T. Sirivedhin, Reclamation of produced water for beneficial use, *Sep. Sci. Technol.* 40 (2005) 185–200.
- [62] C.F. Garbutt, Innovative treating processes allow steam flooding with poor quality oilfield water, in: SPE Annual Technical Conference and Exhibition, San Antonio, Texas, USA, 5–8 October, 1997.
- [63] C.F. Garbutt, Water treatment process for reducing the hardness of an oilfield produced water, US Patent No. 5,879,562 (1999).
- [64] F.S. Zhou, M.F. Zhao, W.X. Ni, Y.S. Dang, C.S. Pu, F.J. Lu, Inorganic polymeric flocculent FMA for purifying oilfield produced water: preparation and uses, *Oilfield Chem.* 17 (2000) 256–259.
- [65] M. Houcine, Solution for heavy metals decontamination in produced water/case study in southern Tunisia, in: International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production, Kuala Lumpur, Malaysia, 20–22 March, 2002.
- [66] T.C. Frankiewicz, J. Gerlach, Removal of hydrocarbons, mercury and arsenic from oil-field produced water, US Patent No. 6,117,333 (2000).
- [67] S. Renou, J.G. Givaudan, S. Poulain, F. Dirassouyan, P. Moulin, Landfill leachate treatment: review and opportunity, *J. Hazard. Mater.* 150 (2008) 468–493.
- [68] H. Ma, B. Wang, Electrochemical pilot-scale plant for oil field produced wastewater by M/C/Fe electrodes for injection, *J. Hazard. Mater.* B132 (2006) 237–243.
- [69] A. Fujishima, K. Honda, Electrochemical photolysis of water at a semiconductor electrode, *Nature* 238 (1972) 37–38.
- [70] E. Bessa, G.L. Sant'Anna Jr., M. Dezotti, Photocatalytic/H₂O₂ treatment of oil field produced waters, *Appl. Catal. B* 29 (2001) 125–134.
- [71] G. Li, T. An, J. Chen, G. Sheng, J. Fu, F. Chen, S. Zhang, H. Zhao, Photoelectrocatalytic decontamination of oilfield produced wastewater containing refractory organic pollutants in the presence of high concentration of chloride ions, *J. Hazard. Mater.* B138 (2006) 392–400.
- [72] G. Li, T. An, X. Nie, G. Sheng, X. Zeng, J. Fu, Z. Lin, E.Y. Zeng, Mutagenicity assessment of produced water during photoelectrocatalytic degradation, *Environ. Toxicol. Chem.* 26 (2007) 416–423.
- [73] M. Adams, I. Campbell, P.K.J. Robertson, Novel photocatalytic reactor development for removal of hydrocarbons from water, *Int. J. Photoenergy* (2008) 1–6, Art. No. 674537.
- [74] Z.G. Yang, N.S. Zhang, Treatment of produced wastewater by flocculation settlement-Fenton oxidation-adsorption method, *J. Xi'an Shiyu Univ. Nat. Sci. Ed.* 20 (2005) 50–53.
- [75] L.R. Morrow, W.K. Martir, H. Aghazeynali, D.E. Wright, Process of treating produced water with ozone, US Patent No. 5,868,945 (1999).

- [76] K.T. Klasson, C. Tsouris, S.A. Jones, M.D. Dinsmore, A.B. Walker, D.W. De Paoli, S. Yiacoumi, V. Viithayaveraj, R.M. Counce, S.M. Robinson, Ozone Treatment of Soluble Organics in Produced Water, <http://www.osti.gov/bridge>, 2002.
- [77] J. McFarlane, W.B. Ridenour, H. Luo, R.D. Hunt, D.W. De Paoli, R.X. Ren, Room temperature ionic liquids for separating organics from produced water, *Sep. Sci. Technol.* 40 (2005) 1245–1265.
- [78] S. Deng, G. Yu, Z. Jiang, R. Zhang, Y.P. Ting, Destabilization of oil droplets in produced water from ASP flooding, *Colloids Surf. A* 252 (2005) 113–119.
- [79] F.H. Holloway, The chemical treatment of offshore oil and gas production, in: *Proceedings of the Offshore Europe Conference*, Aberdeen, United Kingdom, 5–15, September, 1977.
- [80] D.D.C. Freire, M.C. Cammarota, G.L. Sant'Anna, Biological treatment of oil field wastewater in a sequencing batch reactor, *Environ. Technol.* 22 (2001) 1125–1135.
- [81] P. Baldoni-Andrey, N. Lesage, B. Segues, P. Pedenaud, P.L. Dehaene, Impact of high salinity of produced water on the technical feasibility of biotreatment for E&P onshore applications, in: *SPE International Health, Safety & Environment Conference*, Abu Dhabi, UAE, 2–4 April, 2006.
- [82] N. Wei, X.H. Wang, F.K. Li, Y.J. Zhang, Y. Guo, Treatment of high-salt oil field produced water by composite microbial culture, *Urban Environ. Urban Ecol.* 16 (2003) 10–12.
- [83] M.P. Dfaz, S.J.W. Grigson, C.J. Peppiat, G. Burgess, Isolation and characterization of novel hydrocarbon-degrading euryhaline consortia from crude oil and mangrove sediments, *Mar. Biotechnol.* 2 (2000) 522–532.
- [84] G.T. Tellez, N. Nirmalakhandan, Bioreclamation of oilfield produced wastewaters: characterization and feasibility study, in: J.P. Ray, F.R. Engelhardt (Eds.), *Produced Water: Technological/Environmental Issues and Solutions*, Plenum Publishing Corp., New York, 1992, pp. 523–534.
- [85] H.Y. Ng, S.L. Ong, W.J. Ng, Effects of sodium chloride on the performance of a sequencing batch reactor, *J. Environ. Eng.* 131 (2005) 1557–1564.
- [86] I.J. Kang, C.H. Lee, K.J. Kim, Characteristics of microfiltration membranes in a membrane coupled sequencing batch reactor system, *Water Res.* 37 (2003) 1192–1197.
- [87] L.L. Palmer, A.H. Beyer, J. Stock, Biological oxidation of dissolved compounds in oilfield produced water by a field pilot biodisk, *J. Petrol. Technol.* 8308-PA (1981) 1136–1140.
- [88] Q. Li, C. Kang, C. Zhang, Waste water produced from an oilfield and continuous treatment with an oil-degrading bacterium, *Process Biochem.* 40 (2005) 873–877.
- [89] X. Zhao, Y. Wang, Z. Ye, A.G.L. Borthwick, J. Ni, Oil field wastewater treatment in biological aerated filter by immobilized microorganisms, *Process Biochem.* 41 (2006) 1475–1483.
- [90] L.M. Jackson, J.E. Myers, Design and construction of pilot wetlands for produced-water treatment, in: *SPE Annual Technical Conference and Exhibition Denver, Colorado, USA*, 5–8 October, 2003.
- [91] A.H. Beyer, L.L. Palmer, J. Stock, Biological oxidation of dissolved compounds in oilfield-produced water by a pilot aerated lagoon, *JPT J. Petrol. Technol.* 31 (1979) 241–245.
- [92] R.K. Hommel, Formation and physiological role of biosurfactants produced by hydrocarbon-utilizing microorganisms, *Biodegradation* 1 (1990) 107–119.
- [93] Metcalf, Eddy, *Wastewater Engineering: Treatment and Reuse*, 4th ed., McGraw-Hill Inc., New York, 2003.
- [94] J.R. Gallagher, *Anaerobic Biological Treatment Of Produced Water*, <http://www.energystorm.us/Anaerobic.Biological.Treatment.Of.Produced.Water-r54822.html>, 2001.
- [95] C. Gurden, J. Cramwinckel, Application of reedbed technology in production water management, in: *SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production*, Stavanger, Norway, 26–28 June, 2000.
- [96] A. Al Mahruki, B. Alloway, The use of reed-bed technology for treating oil-production waters in the sultanate of Oman, in: *SPE International Health, Safety & Environment Conference*, Abu Dhabi, UAE, 2–4 April, 2006.
- [97] A. Sonune, R. Ghate, Developments in wastewater treatment methods, *Desalination* 167 (2004) 55–63.
- [98] S.S. Madaeni, The application of membrane technology for water disinfection. Review paper, *Water Res.* 33 (1999) 301–308.
- [99] S. Judd, B. Jefferson, *Membranes for Industrial Wastewater Recovery and Reuse*, Elsevier, Oxford, United Kingdom, 2003.
- [100] F.E. Ciarapica, G. Giacchetta, The treatment of produced water in offshore rig: comparison between tradition installations and innovative systems, in: *fifth International Membrane Science & Technology Conference*, University of New South Wales, Sydney, Australia, 10 November, 2003.
- [101] Y. He, Z.W. Jiang, Treating oilfield wastewater: technology review, *Filtr. Sep.* June (2008) 14–16.
- [102] Y.S. Lia, L. Yana, C.B. Xiang, L.J. Hong, Treatment of oily wastewater by organic–inorganic composite tubular ultrafiltration (UF) membranes, *Desalination* 196 (2006) 76–83.
- [103] T. Bilstad, E. Espedal, Membrane separation of produced water, *Water Sci. Technol.* 34 (1996) 239–246.
- [104] J.M. Lee, T. Frankiewicz, Treatment of produced water with an ultrafiltration (UF) membrane—a field trial, in: *SPE Annual Technical Conference and Exhibition*, Dallas, Texas, USA, 9–12 October, 2005.
- [105] M.S.H. Bader, Seawater versus produced water in oil-fields water injection operations, *Desalination* 208 (2007) 159–168.
- [106] K. Shams Ashaghi, M. Ebrahimi, P. Czermak, Ceramic ultra- and nanofiltration membranes for oilfield produced water treatment: a mini review, *Open Environ. J.* 1 (2007) 1–8.
- [107] A.S.C. Chen, J.T. Flynn, R.G. Cook, A.L. Casaday, Removal of oil, grease, and suspended solids from produced water with ceramic crossflow microfiltration, *SPE Prod. Eng.* 6 (1991) 131–136.
- [108] D.B. Burnett, Potential for Beneficial Use of Oil and Gas Produced Water, <http://www.rrc.state.tx.us/commissioners/williams/environment/beneficialuses.pdf>, 2004.
- [109] P. Xu, J.E. Drewes, D. Heil, Beneficial use of co-produced water through membrane treatment: technical-economic assessment, *Desalination* 225 (2008) 139–155.
- [110] A. Zaidi, K. Simms, S. Kok, Use of micro/ultrafiltration for the removal of oil and suspended solids from oilfield brines, *Water Sci. Technol.* 25 (1992) 163–176.
- [111] N. Liu, J. Lu, L. Li, R. Lee, Factors determining the reverse osmosis performance of zeolite membranes on produced water purification, in: *SPE International Symposium on Oilfield Chemistry*, Houston, Texas, USA, 28 February to 2 March, 2007.
- [112] L. Li, N. Liu, B. McPherson, R. Lee, Influence of counter ions on the reverse osmosis through MFI zeolite membranes: implications for produced water desalination, *Desalination* 228 (2008) 217–225.
- [113] L. Liangxiang, T.M. Whitworth, R. Lee, Separation of inorganic solutes from oil-field produced water using a compacted bentonite membrane, *J. Membr. Sci.* 217 (2003) 215–225.
- [114] M. Barrufet, D. Burnett, B. Mareth, Modeling and operation of oil removal and desalting oilfield brines with modular units, in: *SPE Annual Technical Conference and Exhibition*, Dallas, Texas, USA, 9–12 October, 2005.
- [115] C.A. Dyke, Reducing aqueous boron concentrations with reverse osmosis membranes operating at a high pH, *US Patent No.* 5,250,185 (1992).
- [116] F.T. Tao, S. Curtice, R.D. Hobbs, J.L. Sides, J.D. Wieser, C.A. Dyke, D. Tuohy, P.F. Pilger, Reverse osmosis process successfully converts oil field brine into freshwater, *Oil Gas J.* 91 (1993) 88–91.
- [117] N.A. Water Systems, Llc., OPUS Successfully Desalinates Oilfield Produced Water, <http://www.osti.gov/bridge/servlets/purl/822934-oepW00/native/822934.pdf>, 2008.
- [118] X. Qiao, Z. Zhang, J. Yu, X. Ye, Performance characteristics of a hybrid membrane pilot-scale plant for oilfield produced wastewater, *Desalination* 225 (2008) 113–122.
- [119] M. Cakmakce, N. Kayaalp, I. Koyuncu, Desalination of produced water from oil production fields by membrane processes, *Desalination* 222 (2008) 176–186.
- [120] R. Funston, R. Ganesh, L.Y.C. Leong, Evaluation of Technical and Economic Feasibility of Treating Oilfield Produced Water to Create a "New" Water Resource, <http://www.kennedyjenks.com/News.Pubs/GWPC2002.Roger.Funston.pdf>, 2002.
- [121] P.E. Tsang, C.J. Martin, Economic evaluation of treating oilfield produced water for potable use, in: *Thermal Operations and Heavy Oil Symposium*, Bakersfield, USA, 16–18 March, 2004.
- [122] G.F. Doran, F.H. Carini, D.A. Fruth, J.A. Drago, L.Y.C. Leong, Evaluation of technologies to treat oil field produced water to drinking water or reuse quality, in: *SPE Annual Technical Conference and Exhibition*, San Antonio, Texas, USA, 5–8 October, 1997.
- [123] S. Kwon, E.J. Sullivan, L. Katz, K. Kinney, R. Bowman, Pilot-scale test of a produced water-treatment system for initial removal of organic compounds, in: *SPE Annual Technical Conference and Exhibition*, Denver, Colorado, USA, 21–24 September, 2008.
- [124] C. Murray-Gulde, J.E. Heatley, T. Karanfil, J.H. Rodgers Jr., J.E. Myers, Performance of a hybrid reverse osmosis-constructed wetland treatment system for brackish oil field produced water, *Water Res.* 37 (2003) 705–713.
- [125] A. Zaidi, K. Simms, S. Kok, R. Nelson, Recent advances in the application of membrane technology for the removal of oil and suspended solids from produced waters, in: J.P. Ray, F.R. Engelhardt (Eds.), *Produced Water: Technological/Environmental Issues and Solutions*, Plenum Publishing Corp., New York, 1992, pp. 489–502.
- [126] New Logic Research, Inc., Using VSEP to Treat Produced Water. An Effective and Economical Solution, <http://www.vsep.com/pdf/ProducedWater.pdf>, 2004.
- [127] J. Taylor, R.E. Larson, B. Scherer, Treatment of offshore produced water, an effective membrane process, in: *Proceedings of the 1st International Environmental Northern Seas Conference and Exhibition*, Stavanger, Norway, 26–30 August, 1991.
- [128] D.V. Nakles, I. Ortiz, J.R. Frank, An analysis of management strategies for produced waters from natural gas production, in: J.P. Ray, F.R. Engelhardt (Eds.), *Produced Water: Technological/Environmental Issues and Solutions*, Plenum Publishing Corp., New York, 1992, pp. 73–88.
- [129] OSPAR Commission, Background Document Concerning Techniques for the Management of Produced Water from Offshore Installations, <http://www.ospar.org/documents/dbase/publications/p00162.Techniques%20for%20the%20management%20of%20Produced%20Water.pdf>, 2002.
- [130] E.J. Sullivan, R.S. Bowman, L. Katz, K. Kinney, *Water Treatment Technology for Oil and Gas Produced Water*, http://www.unm.edu/~cstp/Reports/H2O_Session.4/4-5.Sullivan.pdf, 2004.
- [131] A. Fakhru'l-Razi, A.R. Pendashteh, A.B. Dayang Radiah, A. Luqman Chuah, S.S. Madaeni, Z.A. Zurina, Treatment of synthetic produced water in SBR coupled membrane with isolated tropical Halophile microorganism consortium, in: *Proceedings of the 8th International Conference on EcoBalance*, Tokyo, Japan, 2008.

- [132] B.M. Johnson, L.E. Kanagy, J.H. Rodgers Jr., J.W. Castle, Chemical, physical, and risk characterization of natural gas storage produced waters, *Water Air Soil Pollut.* 191 (2008) 33–54.
- [133] J.P. Fillo, J.M. Evans, Characterization and management of produced waters from underground natural gas storage reservoirs, in: American Gas Association Operation Section Proceedings, 1990, pp. 448–459.
- [134] United States Environmental Protection Agency (USEPA), EPA Office of Compliance Sector Notebook Project: Profile of the Oil and Gas Extraction Industry. EPA/310-R-99-006, 2000.
- [135] M.C. Shepherd, F.L. Shore, S.K. Mertens, J.S. Gibson, Characterization of produced waters from natural gas production and storage operations: regulatory analysis of a complex matrix, in: J.P. Ray, F.R. Engelhardt (Eds.), *Produced Water: Technological/Environmental Issues and Solutions*, Plenum Publishing Corp., New York, 1992, pp. 163–174.
- [136] P.J.C. Tibbetts, I.T. Buchanan, L.J. Gawel, R. Large, A comprehensive determination of produced water composition, in: J.P. Ray, F.R. Engelhardt (Eds.), *Produced Water: Technological/Environmental Issues and Solutions*, Plenum Publishing Corp., New York, 1992, pp. 97–113.
- [137] J. Mueller, Y. Cen, R.H. Davis, Crossflow microfiltration of oily water, *J. Membr. Sci.* 129 (1997) 221–235.
- [138] J.C. Campos, R.M.H. Borges, A.M.O. Filho, R. Nobrega, G.L. Sant'Anna Jr., Oilfield wastewater treatment by combined microfiltration and biological processes, *Water Res.* 36 (2002) 95–104.