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Review

A Review on the Nanofiltration Process for Treating Wastewaters from the Petroleum Industry

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Abstract: Activities and/or processes in different segments of the petroleum industry, including upstream and downstream, generate aqueous waste streams containing oil and various contaminants that require treatment/purification before release/reuse. Nanofiltration (NF) technology has been approved as an efficient technology for treating wastewater streams from the petroleum industry. The primary critical issues in an NF treatment process can be listed as mitigation of membrane fouling; selection of appropriate pre-treatment process; and selection of a suitable, cost-effective, non-hazardous cleaning strategy. In this study, NF separation mechanisms, membrane fabrication/modification, effective factors on NF performance, and fouling are briefly reviewed. Then, a summary of recent NF treatment studies on various petroleum wastewaters and performance evaluation is presented. Finally, based on the gaps identified in the field, the conclusions and future perspectives are discussed.

Keywords: oily wastewater; produced water; refinery; membrane; nanofiltration; fouling

Citation: Jafarinejad, S.; Esfahani, M.R. A Review on the Nanofiltration Process for Treating Wastewaters from the Petroleum Industry. *Separations* **2021**, *8*, 206. https://doi.org/10.3390/separations8110206

Academic Editor: Mingheng Li

Received: 19 October 2021
Accepted: 2 November 2021
Published: 4 November 2021

1. Introduction

Petroleum (crude oil and natural gas) is one of the world's main energy sources; and it is an essential provider for many other industries [1,2]. Water is used in different segments of the petroleum industry including upstream and downstream for different applications such as production, cooling, washing, processing, etc. [3]. The exploration and production of petroleum, processing of hydrocarbons in refineries and petrochemical plants, and even other activities like storage, transportation, and distribution of petroleum products [2,4,5], can generate aqueous waste streams containing oil and various contaminants that require treatment/purification before release/reuse. If not suitably treated, the oily wastewater streams not only contaminates the environment and endangers water resources and human health but also decreases the reuse capability of oil and water [2,6–15].

Produced water, water produced as a byproduct during the extraction of oil and natural gas, from both oil and gas fields is the petroleum industry's most massive waste stream by volume [16,17]. It has a complex composition consisting of various organic and inorganic compounds [18,19]. There are different approaches regarding the waste management of produced water including (i) avoiding the production of water onto the surface by polymer gels or downhole water separators; (ii) injecting into formations after probable treatment to decrease fouling and bacterial growth; (iii) possible discharging to the environment according to the discharge regulations; (iv) reusing within the petroleum industry operations with minimal treatment; and (v) remarkable treatment for beneficial uses [16,18,20].

In the petroleum industry, a range of wastewater treatment technologies, including primary treatment processes such as physical and physicochemical processes; secondary treatment processes such as suspended and/or attach growth biological processes; and tertiary treatment processes such as sand filtration, membrane processes, ion exchange, chemical oxidation, advanced oxidation processes (AOPs), etc., have been utilized to treat wastewater streams [2,11–14,21–24]. There is an increasing interest in designing the new energy-efficient, cost-effective, reliable, resilient, and sustainable wastewater treatment systems [25].

Pressure-driven membrane processes are the most commercial membrane filtration technology [26]. Based on the membrane pore sizes, these processes have typically been classified into microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) [27]. These membranes have usually been utilized to treat wastewater streams from the petroleum industry by applying high pressure (high energy) across the membranes [28–32]. In comparison with the conventional treatment techniques, the membrane technology offer advantages such as effective removal of oil, compact design, less-necessity for chemical additives [33–37] and stable effluent quality [36]. The feed streams with high oil concentration cannot be treated by MF and UF due to their relatively larger membrane pores, whereas NF and RO, with higher rejection in comparison with MF and UF, suffer from high energy consumption [2,32,38–41]. In the tradeoff between the acceptable rejection and energy-consumption, NF has potential to replace RO membranes because of lower operating pressure and/or energy consumption [27,42–45], relatively lower investment, operation, and maintenance costs [44]. There is a need to comprehensively review treating wastewater streams from the petroleum industry using the NF process. Thus, this study intends to review the treatment of petroleum wastewater streams by NF technology and then, based on the gaps identified in the area, discuss the conclusions and future perspectives.

The remaining sections of this paper are organized as follows. In Section 2, NF separation mechanisms, membrane fabrication/modification, effective factors on NF performance, and fouling are briefly reviewed. Section 3 includes a discussion of recent NF treatment studies on various petroleum wastewaters and performance evaluation. Finally, Section 4 discusses conclusions and future perspectives of this study.

2. Nanofiltration

2.1. Nanofiltration Fundamentals

In the mid-1980s, Eriksson [46] used the term NF for the new class of membranes that their characteristics fall between UF and RO [2,26,46–49]. The pore size and molecular weight cut-off (MWCO) of NF membranes are 1–10 nm [50–52] and 100–2000 Da [26], respectively. The operating pressure is usually 5–35 bar [49]. These membranes are relatively impermeable to divalent ions, dissolved organic matter, pesticides, and other macromolecules, but tend to pass monovalent ions [2,27,51,53,54].

Wetted surface, preferential sorption-capillary, solution-diffusion, charged capillary, and finely porous rejection mechanisms have been presented by Macoun [55] as the major rejection mechanisms. Further information can be found in Macoun [55] and Shon et al. [27]. A combination of charge effect repulsion, solution diffusion, and sieving through micro/nano-pores have been reported as separation mechanisms [2,26,56]. Among the mentioned mechanisms, the sieving and charge effects are two dominant separation mechanisms of NF membranes. Uncharged or high molecular weight solutes are separated by sieving or size exclusion mechanism. Whereas the charged solutes are separated by both sieving and the electrostatic interaction between the solute species and the membrane surface (Donnan phenomenon) [26,37,47,49,52,57,58].

2.2. Nanofiltration Process Applications

NF membranes can relatively reject divalent ions, multivalent ions, organics, starch, sugar, pesticides, herbicides, and other macromolecules [16,54,56]. In comparison with MF and UF processes, this process has higher efficiencies in the reduction of chemical oxygen demand (COD) and total dissolved solids (TDS) and also operates under low pressure (i.e., low energy usage) conditions compared to RO process [59]. Thus, there has been an increasing interest to use NF technology as an effective process in a variety of applications:

- Food industries including dairy [60,61], beverage [62–64], sugar [65,66], vegetable oil [67,68] and plant extracts [49,69];
- Textile industry and dye concentration [49,70–73];
- Biotechnological/pharmaceutical industry [49,50,74–76];
- Water purification: Water softening, removal of natural organic matter, heavy metals, viruses and bacteria from water [37,49,50,77–81]; and
- Wastewater treatment: Olive mill wastewater [82,83], coke wastewater [84], municipal wastewater [85,86], leachate [87,88], car wash wastewater [89], pulp and paper wastewater [90], oily wastewater from the petroleum industry [59], etc.

2.3. Factors Affecting the Nanofiltration Process Performance

NF process performance is significantly influenced by membrane characteristics, feed characteristics, and operational conditions [26]. Membrane characteristics including MWCO, porosity, morphology, charge, and hydrophilicity can dramatically affect the NF process performance. Additionally, membrane performance is strongly influenced by feed characteristics such as the molecular weight, molecular size, geometry, charge, hydrophilicity of the solute and the feed water chemistry (e.g., pH) [26,42,91,92]. Furthermore, operational conditions such as temperature, pressure, and flow rate can impact the separation process [26]. Bellona et al. [42] and Mulyanti and Susanto [26] completely reviewed the effective factors on NF process.

Rahimpour et al. [47] investigated the effect of operating variables including temperature and trans-membrane pressure (TMP) on the permeate flux, COD, and electric conductivity (EC) in NF treating the oily wastewater generated by the washing of gasoline reserving tanks. The permeate flux, COD, and EC removal were enhanced with increasing TMP. COD and EC removal were reduced with an increase in temperature, whereas the permeate flux was increased. Pressures of 15–20 bar and temperatures of 20–30 °C were reported as the optimum conditions for the permeate flux and COD removal [47]. Additionally, Salahi et al. [36] reported the optimum permeate flux of 180.1 $L/m^2 \cdot h$ at feed temperature of 45 °C, TMP of 4 bar, the cross flow velocity of 1.3 m/s, pH of 10 and salt concentration of 11.2 g/L in NF treating the desalter effluent wastewater from Tehran refinery using nano-porous membrane [36]. Furthermore, Hedayatipour et al. [93] investigated the effect of temperature, pH and TMP on removal efficiency of Ba, Ni, Cr, NaCl, and TDS from the effluent of the dewatering process in an oil and gas well drilling industry by NF process. The temperature of 25 °C, the pressure of 170 psi and pH of 4 were reported as optimum conditions which 85.3%, 77.4%, 58.5%, 79.6%, and 56.3% removal efficiencies were obtained for Ba, Ni, Cr, NaCl, and TDS, respectively [93].

2.4. Fabrication and Modification of Nanofiltration Membranes

Surface chemistry, porosity, pore size distribution, physicochemical compatibility with process feeds, lifetime, and cost are key factors to fabricate the NF membranes [49]. In recent years, researchers have focused on fabricating and developing various polymeric, ceramic, and hybrid ceramic-based NF membranes [94]. Each NF membrane type has advantages, disadvantages, and specific applications; however, polymeric NF membranes have been extensively studied due to their availability, easy modification [94], and good film-forming property [95]. Recent advances and research trends in NF membranes fabrication and modification have been reviewed (e.g., Mohammad et al. [50]; Paul and Jons [96]; Oatley-Radcliffe et al. [97]; Ji et al. [95]; Rabbani Esfahani et al. [92]; and Merlet et al. [94]).

Material selection, additive concentrations, and modification techniques can play important roles in obtaining optimal NF membranes [52]. Different materials and techniques have been used to fabricate NF membranes. Materials such as polymer, ceramic, or a hybrid consisting of both may be used in the structure of a membrane from the active (selective) layer to the porous support layer(s). The porous ceramics for NF are composed of oxide materials [94]. Polysulfone (PSF) [98], polydimethylsiloxane (PDMS) [99], polyethersulfone (PES) [100,101], poly(ether ether ketones) (PEEK) [102], poly(vinylidene fluoride) (PVDF), cellulose acetate (CA) [103], aromatic and semi aromatic polyamides [104,105], polybenzimidazole (PBI) [106], polyaniline (PANI) [107], and polyacrylonitrile (PAN) [52,108] have been reported as applied polymers to prepare polymeric NF membranes. Note that both polymeric and ceramic NF membranes used for treating wastewaters from the petroleum industry are discussed in detail in Section 3.

Interfacial polymerization (IP), phase inversion, UV/photo-grafting, electron beam irradiation, plasma treatment, layer-by-layer, etc. are several approaches to fabricate the polymeric NF membranes [50,96]. IP is the common technique to prepare thin film composite (TFC) NF membranes [44,109]. TFC membranes are made of one support layer and one thin active layer on the top of the support layer [110,111]. They are the main type of RO, NF, and forward osmosis (FO) membranes [112,113]. The incorporation of nanoparticles into the TFC membranes results in thin-film nanocomposite (TFN) membranes. Different techniques such as in-situ/interfacial polymerization [114–116] and dip coating methods [117–119] have been reported for the fabrication of TFN membranes. In order to prepare novel TFN membranes with specific characteristic, nanoparticles in the range of 20–200 nm have been incorporated within the ultrathin active layer or support layer during the fabrication process [120].

Plate and frame module, tubular membrane module, spiral wound module, and hollow fiber membrane module are four configurations of NF membrane elements [49].

2.5. Fouling and Control

Membrane fouling is one of the important inevitable challenges in NF process that can be because of blockage of the membrane surface and pores by colloidal, microbiological, and chemical (organic and inorganic) components [26,27,45,47,49,50,121]. It may be reversible or irreversible [56]. Generally, solutes adsorption on the membrane surface or in pores, blockage of pores by solutes, cake layer formation and gel layer formation are forms of fouling [50,122]. Fouling leads to reduction in NF process performance (e.g., flux decline) and cost efficiency [26,50].

Physical, chemical, and hydrodynamical techniques may be used to control membrane fouling [26]. Using pre-treatment processes (e.g., coagulation, flocculation, ozonation, adsorption, MF, UF) upstream of NF, operating the system with high cross-flow velocity, using a cleaning cycle, backwashing or backflushing, and changing the operating temperature are some strategies that may be considered to prevent and mitigate the fouling [27,50,56,123,124]. Note that chemical cleaning may damage the membrane structure [26,125] and suitable cleaning agent and conditions of the cleaning process should be selected to maintain membrane performance [49,126].

Kim et al. [127] studied coagulation-flocculation-sedimentation with and without coagulant and coagulant aids as pre-treatment methods of NF process to treat oil sands process-affected water (OSPW), and concluded that the strategy improves the desalination of OSPW using NF membrane [127]. Additionally, Moser et al. [23] used direct UV and hydrogen peroxide-assisted (UV/H_2O_2) photolysis as pre-treatment methods for NF treating membrane bioreactor (MBR) permeate of a petroleum refinery to mitigate fouling. High quality water was produced using a MBR-H_2O_2/UV-NF system that could be reused in the refinery process (e.g., in cooling systems) [23].

3. Literature Review of Petroleum Industry Wastewater Treatment by Nanofiltration

The required discharge standards from the petroleum industry cannot be reached by common treatment methods. In addition, the need for water reuse in the petroleum industry drive attention to use effective technologies like membrane separation processes (e.g., NF) for better performance and optimized cost [128,129]. However, membrane fouling by oil, sulfides, or bacteria and generation of hazardous reject streams can be drawbacks of these processes [17,129]. In general, several studies have revealed that enhanced flux, minimized membrane fouling, simple cleaning strategy, and chemical and thermal stability of membranes are major issues/barriers for utilization of membrane separation technologies in the petroleum industry wastewater treatment [1,17,130].

Over the last 30 years, NF technology has been used to treat various wastewater streams from the petroleum industry [1,16,23,36,37,44,47,52,53,59,93,127,129–145]. A summary of recent NF treatment studies on various petroleum wastewaters and performance evaluation is listed in Table 1. Various wastewater streams including produced water, OSPW, desalter effluent wastewater from a refinery, MBR permeate from refinery plant, refinery's clarifier effluent, oily wastewater from washing of gasoline reserving tanks, etc. have been successfully treated by NF. Both polymeric and ceramic NF membranes have been applied. In other words, polymeric membranes, such as polyamide (PA) TFC NF membrane (NF-90), piperazine-based semi-aromatic PA TFC NF membrane (NF-270) [136], unmodified and poly(N-isopropylacrylamide) (PNIPAAm) and PNIPAAm-block-poly(ethylene glycol methacrylate) (PPEGMA) modified PA TFC NF (NF-270) membranes [137], nano-porous membrane (polyacrylonitrile) [36], PA-SiO_2 nanocomposite NF membrane [44], PSF-penta-block copolymer (PBC) composite NF membrane [37], PAN NF membrane [52], NF membrane with graphene oxide (GO)/aminated GO (NGO)-incorporated substrate [140], PES-poly acrylic acid (PAA)-ZrO_2 NF membrane [142], etc., and ceramic NF membranes [130,141,143] have been used to treat wastewater streams from the petroleum industry. As presented in Table 1, for instance, almost 100% removal of total suspended solids (TSS), 44.4% removal of TDS, 99.9% removal of oil and grease content, 80.3% removal of COD, 76.9% removal of biological oxygen demand (BOD_5) [36], 72–89% rejection of soluble organics [53], 6–43.7% retention of benzene, 19–89.2% retention of toluene, 48.5–98.5% retention of p-xylene, 48.5–98.5% retention of m-xylene, 30.7–98.7% retention of o-xylene, 21 $\geq$ 99.9% retention of 2-isopropyl phenol, 19.6–99.5% retention of 4- or 3-isopropyl phenol [132], higher than 95% rejection of total organic carbon (TOC), higher than 95% rejection of naphthenic acids (NAs), 62–66% rejection of sodium, higher than 92% rejection of calcium, higher than 90% rejection of magnesium, 95–98% rejection of sulfate, 20–39% rejection of chloride, 58–81% rejection of bicarbonate, and permeate flux of greater than 15 $L/m^2/h$ [133] have been reported in different research studies using various NF membranes.

Peng et al. [133] investigated the performance of three commercially available TFC NF membranes (Deasl-5 from Osmonics/Desal; NF-45 and NF-90 from Dow Chemical) for removal of TOC, NAs, and different ions from OSPW to improve water management in oil sands operation. Among these membranes, Desal-5 was reported to be a suitable membrane for this purpose. Incomplete rejection of monovalent ions of sodium, chloride and bicarbonate (20–80%), higher than 95% rejection of divalent ions (calcium, magnesium, and sulfate), TOC, and NAs were reported for Desal-5. Permeate flux decline of Desal-5 due to fouling was tested in experiments for about 18 h and flux maintaining at 15 $L/m^2/h$ or higher at a pressure of 10.3 bar was reported [133]. In other work, the average efficiency of salt removal from raw OSPW using PA TFC NF membrane (GE Osmonics) was reported to be about 68.9%. The study revealed that OSPW components could bound to the NF membrane surface; and chemical cleaning using both HCL (1 mM) and NaOH (1 mM) showed similar flux recovery ratio (HCl had slightly higher recovery ratio) [127]. These studies [127,133] did not investigate the fouling mechanisms of OSPW desalination by NF; however, they addressed fouling.

Table 1. Summary of recent NF treatment studies on various petroleum wastewaters and performance evaluation.

Membrane	Wastewater	Studied Parameters	Influent Concentration	Major Findings	Reference
NF	Offshore produced water	Soluble organics	176 mg/L	72–89% rejection of soluble organics and 15–20% removal of salts	[53]
NF	Produced water	Oil, sodium, calcium, magnesium, potassium, ammonium, chloride, and sulfate	<1 ppm oil, 9610 ppm sodium, 715 ppm calcium, 412 ppm magnesium, 174 ppm potassium, 110 ppm ammonium, 8010 ppm chloride, and 1090 ppm sulfate.	Concentrations in NF permeate were: non-detectable oil, 5250 ppm sodium, 163 ppm calcium, 115 ppm magnesium, 77 ppm potassium, 68 ppm ammonium, 4710 ppm chloride, and non-detectable sulfate. Recovery was 90–95%.	[16,131,145]
Membranes: UTC-60 (aromatic polyamides) from Toray (Tokyo, Japan); NRT-729HF (polyvinyl alcohol/polyamides), ES-10C (polyamides), and LF-10 (polyvinyl alcohol/polyamides) from Nitto Denko (Osaka, Japan)	Soluble organic pollutants	Benzene, toluene, p-xylene, m-xylene, o-xylene, 2-isopropyl phenol, 4- or 3-isopropyl phenol, etc.	Benzene, toluene, p-xylene, m-xylene, and o-xylene concentrations were 1.25 mg/L; whereas 2-isopropyl phenol and 4- or 3-isopropyl phenol concentrations were 0.05 mg/L.	Retention rates for organic compounds at 0.3 MPa varied among membranes: Benzene, 6–43.7%; toluene, 19–89.2%; p-xylene, 48.5–98.5%; m-xylene, 48.5–98.5%; o-xylene, 30.7–98.7%; 2-isopropyl phenol, 21 -> 99.9%; 4- or 3-isopropyl phenol, 19.6–99.5%, etc. Approximately, retention rates for UTC-60 < NTR-729HF < ES-10C < LF-10.	[132]
TFC NF membranes (Deasl-5 from Osmonics/Desal; NF-45 and NF-90 from Dow Chemical (Midland, MI, USA))	OSPW	TOC, NAs, sodium, calcium, magnesium, sulfate, chloride, and bicarbonate	44 mg/L TOC, 30–57 mg/L NAs, 434–1,170 mg/L sodium, 23.4–46 mg/L calcium, 13–33 mg/L magnesium, 94–1300 mg/L sulfate, 225–760 mg/L chloride, and 545–1040 mg/L bicarbonate + carbonate	>95% rejection of TOC, >95% rejection of NAs, 62–66% rejection of sodium, >92% rejection of calcium, >90% rejection of magnesium, 95–98% rejection of sulfate, 20–39% rejection of chloride, and 58–81% rejection of bicarbonate. Permeate flux was 15 L/m^2/h or higher at a pressure of 10.3 bar.	[133]

Table 1. *Cont.*

Membrane	Wastewater	Studied Parameters	Influent Concentration	Major Findings	Reference
NF-90 (Dow/Filmtec), TFC-S (Koch (MA, USA)), and ESNA (Hydranautics (Oceanside, CA, USA))	Methane produced water	TOC, conductivity, and iodide	TOC, conductivity, and iodide concentrations were 5243 ± 561, 9647 ± 652 µs/cm, and 55.6 ± 10.8 mg/L, respectively.	TOC, conductivity, and iodide rejection efficiencies of NF-90 > TFC-S > ESNA. TOC, conductivity, and iodide rejection efficiencies of NF-90 were 87.6 ± 0.6, 72.7 ± 5.4, and 78.3 ± 1.3, respectively.	[134]
NF-90 (Dow/Filmtec)	Produced water from a natural gas production site in Eastern Montana	TDS, TOC, barium, boron, bromide, chloride, and iodide	5520 ± 718 mg/L TDS, 2 ± 0.5 mg/L barium, 3.8 ± 0.3 mg/L boron, 51 ± 7 mg/L bromide, 3306 ± 854 mg/L chloride, and 50 ± 8 mg/L iodide	Salt rejection was 85.3–94.9%. Concentrations in the NF final product water were 566 mg/L TDS, 0.08 mg/L TOC, 0.02 mg/L barium, 2.6 mg/L boron, 14.0 mg/L bromide, 372 mg/L chloride, and 22.9 mg/L iodide.	[135]
Piperazine-based semi-aromatic polyamide TFC membrane (NF-270) and polyamide TFC membrane (NF-90) from Filmtec (MN, USA)	Produced water from Colorado, USA	TDS and TOC	TDS and TOC were 722–2090 ppm and 68.8–136.4 mg/L, respectively.	NF 270 had the largest membrane pore size; the conductivity, TDS, and TOC of the permeate were the highest.	[136]
NF-200 (Polyamide TFC from Filmtech (MN, USA))	Vakiflar oil produced water	COD, TDS, sodium, chloride, and salinity	1483 mg/L COD, 6510 mg/L TDS, 5169 mg/L sodium, 2949 mg/L chloride, and 6.7% salinity	Effluent concentrations were: 137 mg/L COD, 2240 mg/L TDS, 1059 mg/L sodium, 1200 mg/L chloride, and 2.3% salinity	[1]
Unmodified and poly(N-isopropylacrylamide) (PNIPAAm) and PNIPAAm-block-poly(ethylene glycol methacrylate) (PPEGMA) modified NF-270 polyamide TFC membranes	Coal bed methane produced water	TDS and conductivity	TDS and conductivity were 722 ppm and 1448 µs, respectively.	Effluent TDS and conductivity for unmodified membrane were 648 ppm and 1297 µs, respectively. Whereas effluent TDS and conductivity for one of the modified membrane were 342 ppm and 694 µs, respectively.	[137]
Ceramic NF membrane	Oilfield produced water	Oil and TOC	Oil and TOC were 113 and 94 ppm, respectively.	Oil and TOC removals were 80% and 13%, respectively.	[130]
Polyamide TFC NF membrane from GE Osmonics (Fairfield, CT, USA)	OSPW	Salts		The average efficiency of salt removal from raw OSPW was about 68.9%	[127]

Table 1. *Cont.*

Membrane	Wastewater	Studied Parameters	Influent Concentration	Major Findings	Reference
Polyamide TFC NF commercial membrane (NE2540-90, SAEHAN Corp., Korea) and self-made TFC NF membrane	Oily wastewater from washing of gasoline reserving tanks	COD and EC	The COD and EC of pre-treated wastewater were 2940 ppm and 73 µs/cm, respectively.	The COD and EC removals were 84% and 88% for commercial membrane and 79% and 93% for self-made membrane, respectively.	[47]
NF-90 (Dow Filmtec)	The MBR permeate from REGAP-Gabriel Passos Refinery Plant, Brazil	Ammonia, chloride, calcium, nitrite, COD, TOC, and TDS	30 mg/L ammonia, 573 mg/L chloride, 34 mg/L calcium, 0.66 mg/L nitrite, 440 mg/L COD, 91 mg/L TOC, and 1575 mg/L TDS	98.60% removal of ammonia, 98.75% removal of chloride, 100% removal of calcium, 100% removal of COD, 99.36% removal of TOC, and 98.35% removal of TDS	[23]
Self-made polyacrylonitrile (PAN) NF membrane	Synthetic produced water	oil and salts	10 ppm oil and 6000 ppm of salts	Water flux and overall rejection were 78.8 ($L/m^2 \cdot h$) and 46.2%, respectively.	[52]
Self-made NF membrane with graphene oxide (GO)/aminated GO (NGO)-incorporated substrate	Petrochemical wastewater and shale gas produced water	Ions		Generally, better performance of TFC_{NGO} than TFC_{GO}; remarkable increase of water flux (higher than 24.8%) and similar divalent ion rejection for petrochemical wastewater; better performance in permeability and divalent ion rejections (approximately 6% higher than pristine membrane) for shale gas produced water	[140]
A commercial titania ceramic NF membrane	Recycle water from a Canadian oil sands mine	Ions, TSS, and TOC		High rejection of divalent cations, 75–90% TOC rejection, and almost 100% TSS rejection	[141]
NF (GE Osmonics)	Whiting refinery's clarifier effluent	Mercury		Effluent mercury concentration of <1.3 ppt	[138]
Self-made PA-SiO_2 nanocomposite NF membrane	Oily wastewater from Daqing oilfield	Salts		Nearly 50% salts removal	[44]
Nano-porous membrane (polyacrylonitrile)	Desalter effluent wastewater from Tehran refinery	TSS, TDS, oil, and grease content, COD and BOD_5	250 mg/L TSS, 8200 mg/L TDS, 196 mg/L oil and grease, 456 mg/L COD and 321 mg/L BOD_5	100% removal of TSS, 44.4% removal of TDS, 99.9% removal of oil and grease, 80.3% removal of COD and 76.9% removal of BOD_5	[36]

Table 1. *Cont.*

Membrane	Wastewater	Studied Parameters	Influent Concentration	Major Findings	Reference
NF1 from Amfor Inc. (Amei Ande Membrane Technology Ltd., Beijing, China)	Produced water	TDS, oil and grease, TSS, COD, and TOC	854 mg/L TDS, 2 mg/L oil and grease, 10 mg/L TSS, 96 mg/L COD, and 26.3 mg/L TOC	Effluent concentrations were 520 mg/L TDS, <1 mg/L oil and grease, <1 mg/L TSS, 60 mg/L COD, and 22.9 mg/L TOC	[139]
TFC NF membrane (Sepro Membrane Inc., Oceanside, CA, USA)	Oily wastewater	Oil and magnesium	Oil and magnesium concentrations were 200–2000 and 40–403 ppm, respectively.	95–98% oil rejection and 56–99.8% magnesium rejection	[59]
TFC NF membranes (HL4040F) of polyamide chemistry (GE/Osmonics)	Oilfield produced water	TDS, hydrocarbons, oil droplets, sulfate, silica, boron, and SS	Concentrations of TDS, organics including hydrocarbons, oil droplets, sulfate, silica, boron, and SS were 96,472.6, 268.2, 120.4, 7087.5, 134.4, 29.3, and 20.2 ppm, respectively.	Intermittent chlorination/coagulation/NF combined unit efficiently rejected sulfate, uranium, and other metal cations and polished the removal of SS, bacteria, and organics.	[129]
Self-made polysulphone (PSF)-penta-block copolymer (PBC) composite NF membrane	Engine oil in water emulsion	Oil	500–1000 ppm engine oil in water emulsion	95.5–99.5% oil rejection; and flux recovery of 89–95%	[37]
NF (Polyamide, JCM-1812-50N, USA)	Produced wastewater from dewatering unit of an oil and gas well drilling industry	Ba, Ni, Cr, NaCl and TDS	209 mg/L Ba, 6.2 mg/L Ni, 5.3 mg/L Cr, 14,180 mg/L NaCl and 61,500 mg/L TDS	85.3% removal of Ba, 77.4% removal of Ni, 58.5% removal of Cr, 79.6% removal of NaCl and 56.3% removal of TDS	[93]
Polyethersulfone (PES)-poly acrylic acid (PAA)-ZrO_2 NF membrane	Synthetic wastewater	Polycyclic aromatic hydrocarbon (PAH)		More than 90% PAH rejection rate	[142]
Ceramic NF membranes with γ-Al_2O_3 support and ZrO_2, Al_2O_3 and TiO_2 selective layers (Rauschert Inopor, Veilsdorf, Germany)	Produced water from different SAGD operations in Alberta, Canada	Residual organic matter		Complete removal of non-polar oil components including saturated and aromatic hydrocarbons, approximately 80% removal of polar components, and 95.0–98.3% removal of total solvent extracted material	[143]

BOD_5—biochemical oxygen demand, COD—chemical oxygen demand, EC—electric conductivity, NF—nanofiltration, NAs—naphthenic acids, OSPW—oil sands process-affected water, PAH—polycyclic aromatic hydrocarbon, SAGD—steam assisted gravity drainage, SS—suspended solids, TFC—thin film composite, TOC—total organic carbon, TDS—total dissolved solids, TSS—total suspended solids.

Several studies have been reported for produced water treatment using polymeric [1,16,53,93,129,131,134–136,139,140,145] and ceramic [130,143] NF membranes. In general, application under extreme operating conditions beyond the operating range of typical polymeric membranes, cleaning with aggressive reagents such as organic solvents or hot water steam and long lifespan can be advantages of ceramic membranes [143]. Xu et al. [135] used PA TFC NF membrane (NF-90) to treat produced water from a natural gas production site in Eastern Montana for beneficial use of it by meeting potable and irrigation water quality standards. Salt rejection was 85.3–94.9%. TDS, TOC, barium, boron, bromide, chloride, and iodide concentrations in the NF-90 final product water were 566, 0.08, 0.02, 2.6, 14.0, 372, 22.9 mg/L, respectively. Effluent water from the NF-90 could not meet US Environmental Protection Agency secondary drinking water standards with regard to chloride and TDS [135]. Mondal and Wickramasinghe [136] reported that effluent conductivity, TDS, and TOC of piperazine-based semi-aromatic PA TFC NF membrane (NF-270) were higher than those of the PA TFC NF membrane (NF-90) in treating produced water [136]. In a study [130], oilfield produced water was treated using a ceramic NF membrane and oil and TOC removals were reported to be 80% and 13%, respectively [130]. In other work [143], produced water from different steam assisted gravity drainage (SAGD) operations in Alberta, Canada was treated using ceramic NF membranes with γ-Al_2O_3 support and ZrO_2, Al_2O_3 and TiO_2 selective layers (Rauschert Inopor, Veilsdorf, Germany); and complete removal of non-polar oil components including saturated and aromatic hydrocarbons, approximately 80% removal of polar components, and 95.0–98.3% removal of total solvent extracted material were reported [143].

NF has been used as an effective process for sulfate removal in the petroleum industry especially in offshore oilfields [3,144]. In sulfate removal using NF process, cartridge filters are utilized upstream of the system to reduce pre-treatment upsets [3]. A pilot study (Figure 1) including membrane separation processes (cartridge filter, UF, NF, and two RO units) was conducted by Osmonics Inc. (MN, USA) in 2001 to treat produced water in northern California. Oil, sodium, calcium, magnesium, potassium, ammonium, chloride, and sulfate concentration in influent feed were 10–50, 9610, 715, 412, 174, 110, 8010, and 1090 ppm, respectively. Whereas, oil, sodium, calcium, magnesium, potassium, ammonium, chloride, sulfate concentrations in NF permeate and recovery percent were non-detectable, 5250, 163, 115, 77, 68, 4710 ppm, non-detectable, 90–95%, respectively. More than 80% was reported as the overall system recovery [16,131,145].

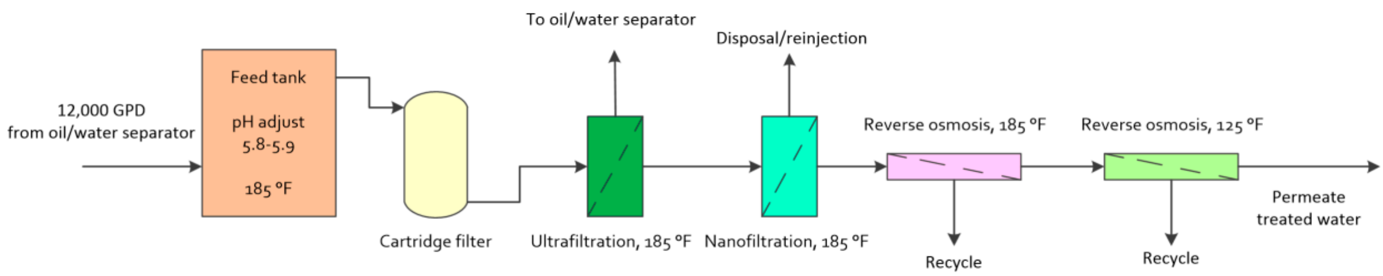

Figure 1. Schematic flow diagram of the GE pilot scale produced water treatment system (modified after [16,131,145]).

Kim et al. [127] used PA TFC NF membrane (GE Osmonics) for desalination of OSPW and reported that coagulation-flocculation-sedimentation pretreatment of OSPW before filtration with NF is an efficient technology to manage water in oil sands operation [127]. Moser et al. [23] studied the effect of AOP (UV/H_2O_2) pretreatment on NF (NF-90, Dow Filmtec) process performance treating MBR permeate of REGAP-Gabriel Passos Refinery Plant, Brazil. The pretreatment mitigated the flux decline because of membrane fouling and improved membrane cleanability. Ammonia, chloride, calcium, COD, TOC, and TDS removal efficiencies were reported to be 99.07%, 98.74%, 100%, 100%, 98.95%, and 98.22%, respectively. They concluded that water produced using the MBR-H_2O_2/UV-NF system could be reused in the refinery process [23]. Khedr [129] proposed the "intermittent chlorination/coagulation/NF" process using PA TFC NF membranes (HL4040F, GE/Osmonics) to filter oilfield-produced water for reinjection; and reported that the process could effectively reject sulfate, uranium, and other metal cations and polish the removal of suspended solids, bacteria, and organics. In addition, the process could prevent the formation of scales and biofilm as well as the related unwanted phenomena [129]. Thus, it seems that NF process should be used in combination with the other separation processes to manage petroleum industry wastewaters [2,129]. Depending on the pretreated oily wastewater quality, this process may provide effluent water for reuse in the petroleum industry applications [19,23,144]. Although the separation efficiency of RO process is better than NF process [19,127,145], the NF process can be cost-effective to reuse water in the petroleum industry [19,144].

Commercially available NF membranes have widely been used for treating wastewater streams from the petroleum industry. However, some studies have been carried out to prepare self-made NF membrane for treatment of petroleum industry wastewaters: PA-SiO_2 nanocomposite NF membrane for desalination of oily wastewater from Daqing oilfield [45]; PSF-PBC composite NF membrane for separation of oil-water emulsion [37]; PAN NF membrane for synthetic produced water treatment [52]; NF membrane with GO/NGO-incorporated substrate for desalination of petrochemical wastewater and shale gas produced water [140]; and PES-PAA-ZrO_2 NF membrane for removal of polycyclic aromatic hydrocarbon (PAH) from synthetic wastewater [142]. Limited information can be found in the literature for modification of commercially available NF membranes for petroleum industry wastewater treatment. In a study carried out by Tomer et al. [137], PNIPAAm and PPEGMA nanolayers were grafted from NF-270 (Filmtec) via surface-initiated atom transfer radical polymerization in order to mitigate fouling in treatment of coal bed methane produced water. Improved permeate water quality and constant flux for modified NF-270 were reported as compared to those of unmodified NF-270 during filtration of produced water [137].

4. Conclusions and Future Perspectives

In this study, recent NF treatment studies on various petroleum wastewaters were reviewed. Key findings of this review are:

- Approximately 100% removal of TSS, 44.4% removal of TDS, 99.9% removal of oil and grease content, 80.3% removal of COD, 76.9% removal of BOD_5 [36], higher than 95% rejection of TOC, higher than 95% rejection of NAs, 62–66% rejection of sodium, higher than 92% rejection of calcium, higher than 90% rejection of magnesium, 95–98% rejection of sulfate, 20–39% rejection of chloride, 58–81% rejection of bicarbonate [133], etc. have been reported in different research studies for treating petroleum wastewaters using various NF membranes.
- NF has the potential to replace RO membranes because of lower operating pressure and/or energy consumption, relatively lower investment, and more economical operation and maintenance costs.
- NF process should be used in combination with other separation processes (e.g., pretreatment processes) to manage petroleum industry wastewaters [2,129]. Depending on the pretreated oily wastewater quality, this process may provide effluent water for reuse in the petroleum industry applications [19,23,144]
- The mitigation of membrane fouling; selection of appropriate pre-treatment technique; and selection of a suitable, cost-effective, non-hazardous cleaning strategy are the vital items in designing of NF process [17].

Further investigations on the enhanced flux, minimized membrane fouling, simple cleaning strategy, and chemical and thermal stability of membranes for long-term operations are still desirable to extensively/efficiently apply NF process for petroleum industry wastewater treatment at full-scale. In particular, further studies on fouling mechanisms of petroleum industry wastewaters (e.g., OSPW) desalination by NF [127] can be beneficial. In addition, studies on the effect of membrane properties such as membrane molecular weight cut-off and surface properties [142,143] on its performance (e.g., NF separation efficiency) in treating oily wastewater are of interest. For instance, incorporating stable and inexpensive nanoparticles in NF membrane manufacturing technology [142] can result in developing/fabricating high performance (e.g., enhanced surface hydrophilicity and fouling resistance) membranes.

Author Contributions: Conceptualization, S.J. and M.R.E.; methodology, S.J. and M.R.E.; software, S.J. and M.R.E.; validation, S.J. and M.R.E.; formal analysis, S.J. and M.R.E.; investigation, S.J. and M.R.E.; resources, S.J. and M.R.E.; data curation, S.J. and M.R.E.; writing—original draft preparation, S.J. and M.R.E.; writing—review and editing, S.J. and M.R.E.; visualization, S.J. and M.R.E.; supervision, S.J. and M.R.E.; project administration, S.J.; funding acquisition, S.J. All authors have read and agreed to the published version of the manuscript.

Funding: S. Jafarinejad acknowledges support from the DoD under grant number W911NF2110222.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: M. Rabbani Esfahani gratefully acknowledges the use of the resources of the Alabama Water Institute and the Department of Chemical and Biological Engineering at The University of Alabama. The comments from the anonymous reviewers are appreciated.

Conflicts of Interest: The authors declare no conflict of interest. The funder had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Çakmakce, M.; Kayaalp, N.; Koyuncu, I. Desalination of produced water from oil production fields by membrane processes. *Desalination* **2008**, *222*, 176–186. [CrossRef]
2. Jafarinejad, S. *Petroleum Waste Treatment and Pollution Control*, 1st ed.; Butterworth-Heinemann: Oxford, UK, 2017.
3. Adham, S.; Hussain, A.; Minier-Matar, J.; Janson, A.; Sharma, R. Membrane applications and opportunities for water man-agement in the oil & gas industry. *Desalination* **2018**, *440*, 2–17.
4. Cholakov, G.S. Control of pollution in the petroleum industry. *Pollut. Control Technol.* **2010**, *3*, 1–10.
5. Macini, P.; Mesini, E. The petroleum upstream industry: Hydrocarbon exploration and production, in petroleum engineer-ing-upstream. *Encycl. Life Suport Syst.* **2011**, *3*, 1–76.
6. Zhong, J.; Sun, X.; Wang, C. Treatment of oily wastewater produced from refinery processes using flocculation and ceramic membrane filtration. *Sep. Purif. Technol.* **2003**, *32*, 93–98. [CrossRef]
7. Ghorbanian, M.; Moussavi, G.; Farzadkia, M. Investigating the performance of an up-flow anoxic fixed-bed bioreactor and a sequencing anoxic batch reactor for the biodegradation of hydrocarbons in petroleum-contaminated saline water. *Int. Biodeterior. Biodegradation* **2014**, *90*, 106–114. [CrossRef]
8. Yu, L.; Han, M.; He, F. A review of treating oily wastewater. *Arab. J. Chem.* **2017**, *10*, S1913–S1922. [CrossRef]
9. Jafarinejad, S.; Faraji, M.; Jafari, P.; Mokhtari-Aliabad, J. Removal of lead ions from aqueous solutions using novel-modified magnetic nanoparticles: Optimization, isotherm, and kinetics studies. *Desalin. Water Treat.* **2017**, *92*, 267–274. [CrossRef]
10. Jafarinejad, S. Cost-effective catalytic materials for AOP treatment units. In *Applications of Advanced Oxidation Processes (AOPs) in Drinking Water Treatment. The Handbook of Environmental Chemistry*; Gil, A., Galeano, L., Vicente, M., Eds.; Springer: Cham, Switzerland, 2017.
11. Jafarinejad, S. A comprehensive study on the application of reverse osmosis (RO) technology for the petroleum industry wastewater treatment. *J. Water Environ. Nanotechnol.* **2017**, *2*, 243–264.
12. Jafarinejad, S. Activated sludge combined with powdered activated carbon (PACT process) for the petroleum industry wastewater treatment: A review. *Chem. Int.* **2017**, *3*, 268–277.
13. Jafarinejad, S. Recent developments in the application of sequencing batch reactor (SBR) technology for the petroleum indus-try wastewater treatment. *Chem. Int.* **2017**, *3*, 342–350.
14. Jafarinejad, S. Simulation for the performance and economic evaluation of conventional activated sludge process replacing by sequencing batch reactor technology in a petroleum refinery wastewater treatment plant. *Chem. Eng.* **2019**, *3*, 45. [CrossRef]
15. Tummons, E.N.; Hejase, C.A.; Yang, Z.; Chew, J.W.; Bruening, M.L.; Tarabara, V.V. Oil droplet behavior on model nanofil-tration membrane surfaces under conditions of hydrodynamic shear and salinity. *J. Colloid Interface Sci.* **2020**, *560*, 247–259. [CrossRef]

16. Arthur, D.J.; Langhus, B.G.; Patel, C. Technical Summary of Oil & Gas Produced Water Treatment Technologies. All Consulting, LLC. 2005, pp. 1–53. Available online: http://www.all-llc.com/publicdownloads/ALLConsulting-WaterTreatmentOptionsReport.pdf (accessed on 23 May 2016).
17. Ashaghi, K.S.; Ebrahimi, M.; Czermak, P. Ceramic ultra- and nanofiltration membranes for oilfield produced water treatment: A mini review. *Open Environ. Sci.* **2007**, *1*, 1–8. [CrossRef]
18. Igunnu, E.T.; Chen, G.Z. Produced water treatment technologies. *Int. J. Low-Carbon Technol.* **2012**, *9*, 157–177. [CrossRef]
19. Nasiri, M.; Jafari, I.; Parniankhoy, B. Oil and gas produced water management: A review of treatment technologies, challenges, and opportunities. *Chem. Eng. Commun.* **2017**, *204*, 990–1005. [CrossRef]
20. Fakhru'L-Razi, A.; Pendashteh, A.; Abdullah, L.C.; Biak, D.R.A.; Madaeni, S.S.; Abidin, Z.Z. Review of technologies for oil and gas produced water treatment. *J. Hazard. Mater.* **2009**, *170*, 530–551. [CrossRef]
21. IPIECA. Petroleum refining water/wastewater use and management. IPIECA. *Oper. Best Pract. Ser.* **2010**, 1–55. Available online: https://www.ipieca.org/resources/good-practice/petroleum-refining-water-wastewater-use-and-management/ (accessed on 15 October 2021).
22. Barthe, P.; Chaugny, M.; Roudier, S.; Delgado Sancho, L. *Best Available Techniques (BAT) Reference Document for the Refining of Mineral Oil and gas. Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control)*; EUR 27140; Publications Office of the European Union: Luxembourg, 2015; JRC94879. Available online: https://publications.jrc.ec.europa.eu/repository/handle/JRC94879 (accessed on 15 October 2021).
23. Moser, P.B.; Ricci, B.C.; Reis, B.G.; Neta, L.S.; Cerqueira, A.C.; Amaral, M. Effect of MBR-H2O2/UV hybrid pretreatment on nanofiltration performance for the treatment of petroleum refinery wastewater. *Sep. Purif. Technol.* **2018**, *192*, 176–184. [CrossRef]
24. Jafarinejad, S.; Vahdat, N. Non-catalytic and catalytic supercritical water oxidation of phenol in the wastewaters of petroleum and other industries. In *Advanced Nanotechnology and Application of Supercritical Fluids, Nanotechnology in the Life Sciences*; Inamuddin, A.M., Asiri, Eds.; Springer: Cham, Switzerland, 2020.
25. Jafarinejad, S. A framework for the design of the future energy-efficient, cost-effective, reliable, resilient, and sustainable full-scale wastewater treatment plants. *Curr. Opin. Environ. Sci. Health* **2020**, *13*, 91–100. [CrossRef]
26. Mulyanti, R.; Susanto, H. Wastewater treatment by nanofiltration membranes. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *142*, 012017. [CrossRef]
27. Shon, H.K.; Phuntsho, S.; Chaudhary, D.S.; Vigneswaran, S.; Cho, J. Nanofiltration for water and wastewater treatment—A mini review. *Drink Water Eng. Sci.* **2013**, *6*, 47–53. [CrossRef]
28. Gryta, M.; Karakulski, K.; Morawski, A.W. Purification of oily wastewater by hybrid UF/MD. *Water Res.* **2001**, *35*, 3665–3669. [CrossRef]
29. Chakrabarty, B.; Ghoshal, A.K.; Purkait, M.K. Ultrafiltration of stable oil-in-water emulsion by polysulfone membrane. *J. Membr. Sci.* **2008**, *325*, 427–437. [CrossRef]
30. Abbasi, M.; Salahi, A.; Mirfendereski, S.M.; Mohammadi, T.; Pak, A. Dimensional analysis of permeation flux for microfiltration of oily wastewaters using mullite ceramic membranes. *Desalination* **2010**, *252*, 113–119. [CrossRef]
31. Ahmad, N.A.; Goh, P.S.; Karim, Z.A.; Ismail, A.F. Thin film composite membrane for oily waste water treatment: Recent advances and challenges. *Membranes* **2018**, *8*, 86. [CrossRef]
32. Lee, W.; Goh, P.; Lau, W.; Ong, C.S.; Ismail, A. Antifouling zwitterion embedded forward osmosis thin film composite membrane for highly concentrated oily wastewater treatment. *Sep. Purif. Technol.* **2019**, *214*, 40–50. [CrossRef]
33. Hua, F.L.; Tsang, Y.F.; Wang, Y.J.; Chan, S.Y.; Chua, H.; Sin, S.N. Performance study of ceramic microfiltration membrane for oily wastewater treatment. *Chem. Eng. J.* **2007**, *128*, 169–175. [CrossRef]
34. Cui, J.; Zhang, X.; Liu, H.; Liu, S.; Yeung, K.L. Preparation and application of zeolite/ceramic microfiltration membranes for treatment of oil contaminated water. *J. Membr. Sci.* **2008**, *325*, 420–426. [CrossRef]
35. Ebrahimi, M.; Willershausen, D.; Ashaghi, K.S.; Engel, L.; Placido, L.; Mund, P.; Bolduan, P.; Czermak, P. Investigations on the use of different ceramic membranes for efficient oil-field produced water treatment. *Desalination* **2010**, *250*, 991–996. [CrossRef]
36. Salahi, A.; Noshadi, I.; Badrnezhad, R.; Kanjilal, B.; Mohammadi, T. Nano-porous membrane process for oily wastewater treatment: Optimization using response surface methodology. *J. Environ. Chem. Eng.* **2013**, *1*, 218–225. [CrossRef]
37. Muppalla, R.; Jewrajka, S.K.; Reddy, A.V.R. Fouling resistant nanofiltration membranes for the separation of oil–water emul-sion and micropollutants from water. *Sep. Purif. Technol.* **2015**, *143*, 125–134. [CrossRef]
38. Kasemset, S.; Lee, A.; Miller, D.J.; Freeman, B.D.; Sharma, M.M. Effect of polydopamine deposition conditions on fouling resistance, physical properties, and permeation properties of reverse osmosis membranes in oil/water separation. *J. Membr. Sci.* **2013**, *425–426*, 208–216. [CrossRef]
39. Hickenbottom, K.L.; Hancock, N.T.; Hutchings, N.R.; Appleton, E.W.; Beaudry, E.G.; Xu, P.; Cath, T.Y. Forward osmosis treatment of drilling mud and fracturing wastewater from oil and gas operations. *Desalination* **2013**, *312*, 60–66. [CrossRef]
40. Duong, P.H.H.; Chung, T.S. Application of thin film composite membranes with forward osmosis technology for the separation of emulsified oil-water. *J. Membr. Sci.* **2014**, *452*, 117–126. [CrossRef]
41. Zhang, X.; Tian, J.; Gao, S.; Zhang, Z.; Cui, F.; Tang, C.Y. In situ surface modification of thin film composite forward osmosis mem-branes with sulfonated poly (arylene ether sulfone) for anti-fouling in emulsified oil/water separation. *J. Membr. Sci.* **2017**, *527*, 26–34. [CrossRef]

42. Bellona, C.; Drewes, J.E.; Xu, P.; Amy, G. Factors affecting the rejection of organic solutes during NF/RO treatment—A literature review. *Water Res.* **2004**, *38*, 2795–2809. [CrossRef]
43. Hilal, N.; A1-Zoubi, H.; Darwish, N.A. A comprehensive review of nanofiltration membranes: Treatment, pretreatment, modelling, and atomic force microscopy. *Desalination* **2004**, *170*, 281–308. [CrossRef]
44. Jin, L.; Yu, S.; Shi, W.; Yi, X.; Sun, N.; Ge, Y.; Ma, C. Synthesis of a novel composite nanofiltration membrane incorporated SiO_2 nanoparticles for oily wastewater desalination. *Polymer* **2012**, *53*, 5295–5303. [CrossRef]
45. Jafarinejad, S. Recent advances in nanofiltration process and use of it for oily wastewater treatment. In Proceedings of the 1st International Conference on Environmental Engineering (eiconf), Tehran, Iran, 28 January 2015.
46. Eriksson, P. Nanofiltration extends the range of membrane filtration. *Environ. Prog.* **1988**, *7*, 58–62. [CrossRef]
47. Rahimpour, A.; Rajaeian, B.; Hosienzadeh, A.; Madaeni, S.S.; Ghoreishi, F. Treatment of oily wastewater produced by washing of gasoline reserving tanks using self-made and commercial nanofiltration membranes. *Desalination* **2011**, *265*, 190–198. [CrossRef]
48. Shahmansouri, A.; Bellona, C. Nanofiltration technology in water treatment and reuse: Applications and costs. *Water Sci. Technol.* **2015**, *71*, 309–319. [CrossRef] [PubMed]
49. Abdel-Fatah, M.A. Nanofiltration systems and applications in wastewater treatment: Review article. *Ain. Shams. Eng. J.* **2018**, *9*, 3077–3092. [CrossRef]
50. Mohammad, A.; Teow, Y.; Ang, W.L.; Chung, Y.T.; Oatley-Radcliffe, D.; Hilal, N. Nanofiltration membranes review: Recent advances and future prospects. *Desalination* **2015**, *356*, 226–254. [CrossRef]
51. Ikhsan, S.N.W.; Yusof, N.; Aziz, F.; Misdan, N. A review of oilfield wastewater treatment using membrane filtration over conventional technology. *Malaysian J. Anal. Sci.* **2017**, *21*, 643–658.
52. Shahriari, H.R.; Hosseini, S.S. Experimental and statistical investigation on fabrication and performance evaluation of struc-turally tailored PAN nanofiltration membranes for produced water treatment. *Chem. Eng. Process. Process. Intensif.* **2020**, *147*, 107766. [CrossRef]
53. Dyke, C.A.; Bartels, C.R. Removal of organics from offshore produced waters using nanofiltration membrane technology. *Environ. Prog.* **1990**, *9*, 183–186. [CrossRef]
54. Allen, E.W. Process water treatment in Canada's oil sands industry: II. A review of emerging technologies. *J. Environ. Eng. Sci.* **2008**, *7*, 499–524. [CrossRef]
55. Macoun, R.G. The Mechanisms of Ionic Rejection in Nanofiltration, Chemical Engineering. Ph.D. Thesis, University of New South Wales, Sydney, Australia, 1998.
56. Duraisamy, R.T.; Beni, A.H.; Henni, A. Chapter 9: State of the art treatment of produced water, In: Water treatment, Walid Elshorbagy and Rezaul Kabir Chowdhury. *Intech Open* **2013**, 199–222. Available online: https://www.intechopen.com/chapters/41954 (accessed on 18 October 2021). [CrossRef]
57. Orecki, A.; Tomaszewska, M. The oily wastewater treatment using the nanofiltration process. *Pol. J. Chem. Technol.* **2007**, *9*, 40–42. [CrossRef]
58. Rabbani Esfahani, M.; Tyler, J.L.; Stretz, H.A.; Wells, M.J.M. Effects of a dual nanofiller, nano-TiO2 and MWCNT, for polysul-fone-based nanocomposite membranes for water purification. *Desalination* **2015**, *372*, 47–56. [CrossRef]
59. Abadikhah, H.; Ashtiani, F.Z.; Fouladitajar, A. Nanofiltration of oily wastewater containing salt; experimental studies and opti-mization using response surface methodology. *Desalin. Water Treat.* **2015**, *56*, 2783–2796.
60. Fernández, P.; Riera, F.A.; Álvarez, R.; Álvarez, S. Nanofiltration regeneration of contaminated single-phase detergents used in the dairy industry. *J. Food Eng.* **2010**, *97*, 319–328. [CrossRef]
61. Rice, G.; Barber, A.R.; O'Connor, A.J.; Pihlajamaki, A.; Nystrom, M.; Stevens, G.W.; Kentish, S.E. The influence of dairy salts on nanofiltration membrane charge. *J. Food Eng.* **2011**, *107*, 164–172. [CrossRef]
62. Banvolgyi, S.; Kiss, I.; Bekassy-Molnar, E.; Vatai, G. Concentration of red wine by nanofiltration. *Desalination* **2006**, *198*, 8–15. [CrossRef]
63. Sotoft, L.F.; Christensen, K.V.; Andrésen, R.; Norddahl, B. Full scale plant with membrane based concentration of blackcurrant juice on the basis of laboratory and pilot scale tests. *Chem. Eng. Process. Process. Intensif.* **2012**, *54*, 12–21. [CrossRef]
64. Salgado, C.; Palacio, L.; Carmona, F.; Hernández, A.; Prádanos, P. Influence of low and high molecular weight compounds on the permeate flux decline in nanofiltration of red grape must. *Desalination* **2013**, *315*, 124–134. [CrossRef]
65. Ahsan, L.; Jahan, M.S.; Ni, Y. Recovering/concentrating of hemicellulosic sugars and acetic acid by nanofiltration and reverse osmosis from prehydrolysis liquor of kraft based hardwood dissolving pulp process. *Bioresour. Technol.* **2014**, *155*, 111–115. [CrossRef]
66. Moreno-Vilet, L.; Bonnin-Paris, J.; Bostyn, S.; Ruiz-Cabrera, M.; Santillán, M.M. Assessment of sugars separation from a model carbohydrates solution by nanofiltration using a design of experiments (DoE) methodology. *Sep. Purif. Technol.* **2014**, *131*, 84–93. [CrossRef]
67. Tres, M.V.; Ferraz, H.C.; Dallago, R.M.; Di Luccio, M.; Oliveira, J.V. Characterization of polymeric membranes used in vegetable oil/organic solvents separation. *J. Membr. Sci.* **2010**, *362*, 495–500. [CrossRef]
68. Firman, L.R.; Ochoa, N.A.; Marchese, J.; Pagliero, C.L. Deacidification and solvent recovery of soybean oil by nanofiltration mem-branes. *J. Membr. Sci.* **2013**, *431*, 187–196. [CrossRef]
69. Pan, B.; Yan, P.; Zhu, L.; Li, X. Concentration of coffee extract using nanofiltration membranes. *Desalination* **2013**, *317*, 127–131. [CrossRef]

70. Zahrim, A.; Tizaoui, C.; Hilal, N. Coagulation with polymers for nanofiltration pre-treatment of highly concentrated dyes: A review. *Desalination* **2011**, *266*, 1–16. [CrossRef]
71. Ellouze, E.; Tahri, N.; Ben Amar, R. Enhancement of textile wastewater treatment process using Nanofiltration. *Desalination* **2012**, *286*, 16–23. [CrossRef]
72. Shao, L.; Cheng, X.Q.; Liu, Y.; Quan, S.; Ma, J.; Zhao, S.Z.; Wang, K.Y. Newly developed nanofiltration (NF) composite membranes by interfacial polymerization for Safranin O and Aniline blue removal. *J. Membr. Sci.* **2013**, *430*, 96–105. [CrossRef]
73. Ong, Y.K.; Li, F.Y.; Sun, S.P.; Zhao, B.W.; Liang, C.Z.; Chung, T.S. Nanofiltration hollow fiber membranes for textile wastewater treat-ment: Lab-scale and pilot-scale studies. *Chem. Eng. Sci.* **2014**, *114*, 51–57. [CrossRef]
74. Koyuncu, I.; Arikan, O.A.; Wiesner, M.R.; Rice, C. Removal of hormones and antibiotics by nanofiltration membranes. *J. Membr. Sci.* **2008**, *309*, 94–101. [CrossRef]
75. Székely, G.; Bandarra, J.; Heggie, W.; Sellergren, B.; Ferreira, F.C. Organic solvent nanofiltration: A platform for removal of geno toxins from active pharmaceutical ingredients. *J. Membr. Sci.* **2011**, *381*, 21–33. [CrossRef]
76. Martínez, M.B.; Van der Bruggen, B.; Negrin, Z.R.; Alconero, P.L. Separation of a high-value pharmaceutical compound from waste ethanol by nanofiltration. *J. Ind. Eng. Chem.* **2012**, *18*, 1635–1641. [CrossRef]
77. Fang, W.; Shi, L.; Wang, R. Interfacially polymerized composite nanofiltration hollow fiber membranes for low-pressure water softening. *J. Membr. Sci.* **2013**, *430*, 129–139. [CrossRef]
78. Fang, W.; Shi, L.; Wang, R. Mixed polyamide-based composite nanofiltration hollow fiber membranes with improved low-pressure water softening capability. *J. Membr. Sci.* **2014**, *468*, 52–61. [CrossRef]
79. Chang, F.-F.; Liu, W.-J.; Wang, X.-M. Comparison of polyamide nanofiltration and low-pressure reverse osmosis membranes on As(III) rejection under various operational conditions. *Desalination* **2014**, *334*, 10–16. [CrossRef]
80. Koutahzadeh, N.; Esfahani, M.R.; Bailey, F.; Taylor, A.; Esfahani, A.R. Enhanced performance of polyhedral oligomeric silsesquioxanes/polysulfone nanocomposite membrane with improved permeability and antifouling properties for water treatment. *J. Environ. Chem. Eng.* **2018**, *6*, 5683–5692. [CrossRef]
81. Rabbani Esfahani, M.; Koutahzadeh, N.; Esfahani, A.R.; Firouzjaei, M.D.; Anderson, B.; Peck, L. A novel gold nanocomposite membrane with enhanced permeation, rejection and self-cleaning ability. *J. Membr. Sci.* **2019**, *573*, 309–319. [CrossRef]
82. Paraskeva, C.; Papadakis, V.; Tsarouchi, E.; Kanellopoulou, D.; Koutsoukos, P. Membrane processing for olive mill wastewater fractionation. *Desalination* **2007**, *213*, 218–229. [CrossRef]
83. Coskun, T.; Debik, E.; Demir, N.M. Treatment of olive mill wastewaters by nanofiltration and reverse osmosis membranes. *Desalination* **2010**, *259*, 65–70. [CrossRef]
84. Korzenowski, C.; Minhalma, M.; Bernardes, A.M.; Ferreira, J.Z.; De Pinho, M.N. Nanofiltration for the treatment of coke plant ammoniacal wastewaters. *Sep. Purif. Technol.* **2011**, *76*, 303–307. [CrossRef]
85. Bunani, S.; Yörükoğlu, E.; Sert, G.; Yüksel, Ü.; Yüksel, M.; Kabay, N. Application of nanofiltration for reuse of municipal wastewater and quality analysis of product water. *Desalination* **2013**, *315*, 33–36. [CrossRef]
86. Cuevas, S.M.; Oller, I.; Agüera, A.; Llorca, M.; Pérez, J.A.S.; Malato, S. Combination of nanofiltration and ozonation for the remediation of real municipal wastewater effluents: Acute and chronic toxicity assessment. *J. Hazard. Mater.* **2017**, *323*, 442–451. [CrossRef]
87. Linde, K.; Jönsson, A.-S. Nanofiltration of salt solutions and landfill leachate. *Desalination* **1995**, *103*, 223–232. [CrossRef]
88. Peters, T. Purification of landfill leachate with reverse osmosis and NF. *Desalination* **1998**, *119*, 289–293. [CrossRef]
89. Lau, W.J.; Ismail, A.F.; Firdaus, S. Car wash industry in Malaysia: Treatment of car wash effluent using ultrafiltration and nano-filtration membranes. *Sep. Purif. Technol.* **2013**, *104*, 26–31. [CrossRef]
90. Beril Gönder, Z.; Arayici, S.; Barlas, H. Advanced treatment of pulp and paper mill wastewater by nanofiltration process: Effects of operating conditions on membrane fouling. *Sep. Purif. Technol.* **2011**, *76*, 292–302. [CrossRef]
91. Rabbani Esfahani, M.; Stretz, H.A.; Wells, M.J.M. Abiotic reversible self-assembly of fulvic and humic acid aggregates in low electrolytic conductivity solutions by dynamic light scattering and zeta potential investigation. *Sci. Total Environ.* **2015**, *537*, 81–92. [CrossRef] [PubMed]
92. Rabbani Esfahani, M.; Aktij, S.A.; Dabaghian, Z.; Firouzjaei, M.D.; Rahimpour, A.; Eke, J.; Escobar, I.C.; Abolhassani, M.; Greenlee, L.F.; Esfahani, A.R.; et al. Nanocomposite membranes for water separation and purification: Fabrication, modification, and applications. *Sep. Purif. Technol.* **2019**, *213*, 456–499. [CrossRef]
93. Hedayatipour, M.; Jaafarzadeh, N.; Ahmadmoazzam, M. Removal optimization of heavy metals from effluent of sludge dewatering process in oil and gas well drilling by nanofiltration. *J. Environ. Manag.* **2017**, *203*, 151–156. [CrossRef] [PubMed]
94. Merlet, R.B.; Pizzoccaro, M.-A.; Nijmeijer, A.; Winnubst, L. Hybrid ceramic membranes for organic solvent nanofiltration: State-of-the-art and challenges. *J. Membr. Sci.* **2020**, *599*, 117839. [CrossRef]
95. Ji, Y.L.; Qian, W.J.; Yu, Y.W.; An, Q.F.; Liu, L.F.; Zhou, Y.; Gao, C.J. Recent developments in nanofiltration membranes based on nanomaterials. *Chin. J. Chem. Eng.* **2017**, *25*, 1639–1652. [CrossRef]
96. Paul, M.; Jons, S.D. Chemistry and fabrication of polymeric nanofiltration membranes: A review. *Polymer* **2016**, *103*, 417–456. [CrossRef]
97. Oatley-Radcliffe, D.L.; Walters, M.; Ainscough, T.J.; Williams, P.M.; Mohammad, A.W.; Hilal, N. Nanofiltration membranes and processes: A review of research trends over the past decade. *J. Water Process Eng.* **2017**, *19*, 164–171. [CrossRef]

98. Maurya, S.; Parashuram, K.; Singh, P.; Ray, P.; Reddy, A. Preparation of polysulfone–polyamide thin film composite hollow fiber nanofiltration membranes and their performance in the treatment of aqueous dye solutions. *Desalination* **2012**, *304*, 11–19. [CrossRef]
99. Bhanushali, D.; Kloos, S.; Kurth, C.; Bhattacharyya, D. Performance of solvent-resistant membranes for non-aqueous systems: Solvent permeation results and modeling. *J. Membr. Sci.* **2001**, *189*, 1–21. [CrossRef]
100. Ernst, M.; Bismarck, A.; Springer, J.; Jekel, M. Zeta-potential and rejection rates of a polyethersulfone nanofiltration membrane in single salt solutions. *J. Membr. Sci.* **2000**, *165*, 251–259. [CrossRef]
101. Shahmirzadi, M.A.A.; Hosseini, S.S.; Ruan, G.; Tan, N.R. Tailoring PES nanofiltration membranes through systematic investigations of prominent design, fabrication and operational parameters. *RSC Adv.* **2015**, *5*, 49080–49097. [CrossRef]
102. Da Silva Burgal, J.; Peeva, L.G.; Kumbharkar, S.; Livingston, A. Organic solvent resistant poly(ether-ether-ketone) nanofiltration membranes. *J. Membr. Sci.* **2015**, *479*, 105–116. [CrossRef]
103. Su, J.; Yang, Q.; Teo, J.F.; Chung, T.-S. Cellulose acetate nanofiltration hollow fiber membranes for forward osmosis processes. *J. Membr. Sci.* **2010**, *355*, 36–44. [CrossRef]
104. Li, L.; Zhang, S.; Zhang, X. Preparation and characterization of poly (piperazineamide) composite nanofiltration membrane by interfacial polymerization of 3,3′,5,5′-biphenyl tetraacyl chloride and piperazine. *J. Membr. Sci.* **2009**, *335*, 133–139. [CrossRef]
105. Jegal, J.; Min, S.G.; Lee, K.H. Factors affecting the interfacial polymerization of polyamide active layers for the formation of pol-yamide composite membranes. *J. Appl. Polym. Sci.* **2002**, *86*, 2781–2787. [CrossRef]
106. Valtcheva, I.B.; Kumbharkar, S.C.; Kim, J.F.; Bhole, Y.; Livingston, A.G. Beyond polyimide: Crosslinked polybenzimidazole membranes for organic solvent nanofiltration (OSN) in harsh environments. *J. Membr. Sci.* **2014**, *457*, 62–72. [CrossRef]
107. Sairam, M.; Loh, X.X.; Bhole, Y.; Sereewatthanawut, I.; Li, K.; Bismarck, A.; Steinke, J.H.G.; Livingston, A.G. Spiral-wound polyaniline membrane modules for organic solvent nanofiltration (OSN). *J. Membr. Sci.* **2010**, *349*, 123–129. [CrossRef]
108. Hosseini, S.S.; Nazif, A.; Alaei Shahmirzadi, M.A.; Ortiz, I. Fabrication, tuning and optimization of poly (acrilonitryle) nanofiltration membranes for effective nickel and chromium removal from electroplating wastewater. *Sep. Purif. Technol.* **2017**, *187*, 46–59. [CrossRef]
109. Wu, C.; Zhang, S.; Yang, F.; Yan, C.; Jian, X. Preparation and performance of novel thermal stable composite nanofiltration membrane. *Front. Chem. Eng. China* **2008**, *2*, 402–406. [CrossRef]
110. Lau, W.J.; Ismail, A.F.; Misdan, N.; Kassim, M.A. A recent progress in thin film composite membrane: A review. *Desalination* **2012**, *287*, 190–199. [CrossRef]
111. Ismail, A.; Padaki, M.; Hilal, N.; Matsuura, T.; Lau, W. Thin film composite membrane-recent development and future potential. *Desalination* **2015**, *356*, 140–148. [CrossRef]
112. Firouzjaei, M.D.; Shamsabadi, A.A.; Aktij, S.A.; Seyedpour, S.F.; Sharifian, G.M.; Rahimpour, A.; Esfahani, M.R.; Ulbricht, M.; Soroush, M. Exploiting synergetic effects of graphene oxide and a silver-based metal-organic framework to enhance antifouling and anti-biofouling properties of thin-film nanocomposite membranes. *ACS Appl. Mater. Interfaces* **2018**, *10*, 42967–42978. [CrossRef] [PubMed]
113. Mozafari, M.; Seyedpour, S.F.; Salestan, S.K.; Rahimpour, A.; Shamsabadi, A.A.; Firouzjaei, M.D.; Esfahani, M.R.; Tiraferri, A.; Mohsenian, H.; Sangermano, M. Facile Cu-BTC surface modification of thin chitosan film coated polyethersulfone membranes with improved antifouling properties for sustainable removal of manganese. *J. Membr. Sci.* **2019**, *588*, 117200. [CrossRef]
114. Tian, M.; Wang, Y.-N.; Wang, R. Synthesis and characterization of novel high-performance thin film nanocomposite (TFN) FO membranes with nanofibrous substrate reinforced by functionalized carbon nanotubes. *Desalination* **2015**, *370*, 79–86. [CrossRef]
115. Tian, M.; Wang, Y.-N.; Wang, R.; Fane, A.G. Synthesis and characterization of thin film nanocomposite forward osmosis mem-branes supported by silica nanoparticle incorporated nanofibrous substrate. *Desalination* **2017**, *401*, 142–150. [CrossRef]
116. Zargar, M.; Hartanto, Y.; Jin, B.; Dai, S. Polyethylenimine modified silica nanoparticles enhance interfacial interactions and desalination performance of thin film nanocomposite membranes. *J. Membr. Sci.* **2017**, *541*, 19–28. [CrossRef]
117. Kang, G.-D.; Gao, C.-J.; Chen, W.-D.; Jie, X.-M.; Cao, Y.-M.; Yuan, Q. Study on hypochlorite degradation of aromatic polyamide reverse osmosis membrane. *J. Membr. Sci.* **2007**, *300*, 165–171. [CrossRef]
118. Zheng, Y.; Yao, G.; Cheng, Q.; Yu, S.; Liu, M.; Gao, C. Positively charged thin-film composite hollow fiber nanofiltration membrane for the removal of cationic dyes through submerged filtration. *Desalination* **2013**, *328*, 42–50. [CrossRef]
119. Akhtar, F.H.; Kumar, M.; Peinemann, K.-V. Pebax®1657/Graphene oxide composite membranes for improved water vapor separation. *J. Membr. Sci.* **2017**, *525*, 187–194. [CrossRef]
120. Lau, W.; Gray, S.; Matsuura, T.; Emadzadeh, D.; Chen, J.P.; Ismail, A.F. A review on polyamide thin film nanocomposite (TFN) membranes: History, applications, challenges and approaches. *Water Res.* **2015**, *80*, 306–324. [CrossRef]
121. Firouzjaei, M.D.; Seyedpour, S.F.; Aktij, S.A.; Giagnorio, M.; Bazrafshan, N.; Mollahosseini, A.; Samadi, F.; Ahmadalipour, S.; Firouzjaei, F.D.; Esfahani, M.R.; et al. Recent advances in functionalized polymer membranes for biofouling control and mitigation in forward osmosis. *J. Membr. Sci.* **2020**, *596*, 117604. [CrossRef]
122. Rabbani Esfahani, M.; Stretz, H.A.; Wells, M.J.M. Comparing humic acid and protein fouling on polysulfone ultrafiltration membranes: Adsorption and reversibility. *J. Water Proc. Eng.* **2015**, *6*, 83–92. [CrossRef]
123. Lee, J.M.; Frankiewicz, T.C. Treatment of produced water with an ultrafiltration (UF) membrane—A field trial. In Proceedings of the SPE Annual Technical Conference and Exhibition, Dallas, TX, USA, 9–12 October 2005.

124. Koutahzadeh, N.; Esfahani, M.R.; Arce, P.E. Sequential use of UV/H_2O_2—(PSF/TiO2/MWCNT) mixed matrix membranes for dye removal in water purification: Membrane permeation, fouling, rejection, and decolorization. *Environ. Eng. Sci.* **2016**, *33*, 430–440. [CrossRef]
125. Zulaikha, S.; Lau, W.; Ismail, A.; Jaafar, J. Treatment of restaurant wastewater using ultrafiltration and nanofiltration membranes. *J. Water Process. Eng.* **2014**, *2*, 58–62. [CrossRef]
126. Li, Q.; Elimelech, M. Synergistic effects in combined fouling of a loose nanofiltration membrane by colloidal materials and natural organic matter. *J. Membr. Sci.* **2006**, *278*, 72–82. [CrossRef]
127. Kim, E.S.; Liu, Y.; El-Din, M.G. The effects of pretreatment on nanofiltration and reverse osmosis membrane filtration for de-salination of oil sands process-affected water. *Sep. Purif. Technol.* **2011**, *81*, 418–428. [CrossRef]
128. Nicolaisen, B. Developments in membrane technology for water treatment. *Desalination* **2003**, *153*, 355–360. [CrossRef]
129. Khedr, M.G. Nanofiltration of oil field-produced water for reinjection and optimum protection of oil formation. *Desalination Water Treat.* **2014**, *55*, 3460–3468. [CrossRef]
130. Ebrahimi, M.; Ashaghi, K.S.; Engel, L.; Willershausen, D.; Mund, P.; Bolduan, P.; Czermak, P. Characterization and application of different ceramic membranes for the oil-field produced water treatment. *Desalination* **2009**, *245*, 533–540. [CrossRef]
131. GE Infrastructure Water & Process Technologies, Produced Water Pilot Study. 2001.
132. Agenson, K.O.; Oh, J.H.; Urase, T. Retention of a wide variety of organic pollutants by different nanofiltration/reverse osmosis membranes: Controlling parameters to the process. *J. Membr. Sci.* **2003**, *225*, 91–103. [CrossRef]
133. Peng, H.; Volchek, K.; MacKinnon, M.; Wong, W.P.; Brown, C.E. Application on to nanofiltration to water management op-tions for oil sands operation. *Desalination* **2004**, *170*, 137–150. [CrossRef]
134. Xu, P.; Drewes, J.E. Viability of nanofiltration and ultra-low pressure reverse osmosis membranes for multi-beneficial use of methane produced water. *Sep. Purif. Technol.* **2006**, *52*, 67–76. [CrossRef]
135. Xu, P.; Drewes, J.E.; Heil, D. Beneficial use of co-produced water through membrane treatment: Technical-economic assess-ment. *Desalination* **2008**, *225*, 139–155. [CrossRef]
136. Mondal, S.; Wickramasinghe, S.R. Produced water treatment by nanofiltration and reverse osmosis membranes. *J. Membr. Sci.* **2008**, *322*, 162–170. [CrossRef]
137. Tomer, N.; Mondal, S.; Wandera, D.; Wickramasinghe, S.R.; Husson, S.M. Modification of nanofiltration membranes by sur-face-initiated atom transfer radical polymerization for produced water filtration. *Sep. Sci. Technol.* **2009**, *44*, 3346–3368. [CrossRef]
138. Negri, M.; Gillenwater, P.; Urgun Demirtas, M. *Emerging Technologies and Approaches to Minimize Discharges into Lake Michigan Phase 2, Module 3 Report*; Argonne National Laboratory (ANL): USA, 2011.
139. Alzahrani, S.; Mohammad, A.W.; Abdullah, P.; Jaafar, O. Potential tertiary treatment of produced water using highly hydrophilic nanofiltration and reverse osmosis membranes. *J. Environ. Chem. Eng.* **2013**, *1*, 1341–1349. [CrossRef]
140. Kong, F.-X.; Yang, Z.-Y.; Yue, L.-P.; Chen, J.-F.; Guo, C.-M. Nanofiltration membrane with substrate incorporated amine-functionalized graphene oxide for enhanced petrochemical wastewater and shale gas produced water desalination. *Desalination* **2021**, *517*, 115246. [CrossRef]
141. Cabrera, S.M.; Winnubst, L.; Richter, H.; Voigt, I.; Arian Nijmeijer, A. Industrial application of ceramic nanofiltration mem-branes for water treatment in oil sands mines. *Sep. Purif. Technol.* **2021**, *256*, 117821. [CrossRef]
142. Chen, X.; Huang, G.; An, C.; Feng, R.; Huang, C.; Wu, Y. Superwetting polyethersulfone nanoparticles for polycyclic membrane functionalized with ZrO aromatic hydrocarbon removal. *J. Mater. Sci. Technol.* **2021**, *98*, 14–25. [CrossRef]
143. Yang, C.; Kuang, W.; Zhang, G.; Mortazavi, S.; Doiron, A.; Volchek, K.; Lambert, P. Characterization of residual organic matter in oil sands steam assisted gravity drainage produced water treated by ceramic nanofiltration membranes. *J. Pet. Sci. Eng.* **2021**, *208*, 109408. [CrossRef]
144. Munirasu, S.; Haija, M.A.; Banat, F. Use of membrane technology for oil field and refinery produced water treatment: A review. *Process. Saf. Environ. Protec.* **2016**, *100*, 183–202. [CrossRef]
145. Interstate Oil and Gas Compact Commission (IOGCC) and ALL Consulting. *A Guide to Practical Management of Produced Water from Onshore Oil and Gas Operations in the United States, Rep No DE-PS26-04NT15460-02, Prepared for US Department of Energy*; October 2006. Available online: https://iogcc.ok.gov/sites/g/files/gmc836/f/documents/2021/produced_water_guidebook2-2006.pdf (accessed on 21 October 2021).