



Bio-Treatment Technologies of Produced Water: A Review

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HIGHLIGHTS

- It has become essential to develop an appropriate management strategy for PW treatment to avoid environmental impact.
- Microbial biodegradation is known to be effective bioremediation for the disposal of various types of compounds, such as organic in PW
- Aerobic treatment is fast and efficient for the elimination of degradable pollutants.
- Anaerobic treatment is a preferential treatment used to provide clean energy from organic waste

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ABSTRACT

Petroleum is a vital source of energy for most human activities. The growth of the oil and gas sector is associated with releasing a significant amount of produced water (PW) from onshore and offshore fields. Thus, undesirable toxic pollutants in produced water have become a major concern for those concerned with environmental issues. Therefore, interest in recycling and beneficial reuse of pollutants has increased due to large amounts of PW. In general, various physical and chemical technologies and bio-treatments for PW or combined between them are applied. Bio-treatment is preferred due to its efficiency and eco-friendly compared with other PW treatments. To clarify the prospective role of PW bio-treatments, this review highlights the main bio-treatment technologies in aerobic and anaerobic conditions to reduce salinity, organic components, and toxicity from PW. Also, challenges of environmental factors for PW and future research directions are included. Activated sludge is an essential part of aerobic bio-treatments of polluted water as inoculum rich in microbial cells that can degrade pollutants. Membrane bioreactors (MBR), fluidized bed bioreactors (FBBs), aerated biological filter (BAF), and aeration lagoons are also reviewed. Moreover, bio-treatments are extended to include anaerobic conditions. Furthermore, bio-treatment techniques can treat organic compounds of wastewater, especially with low oil concentrations and poor solubility that cannot be treated with conventional treatments.

1. Introduction

Nowadays, petroleum is still the first source of energy on the planet and is irreplaceable in transportation, industries, and electricity generation. Although there are sustainable energy sources such as solar, wind, and biomass, petroleum is an essential energy source [1]. On the other hand, several environmental restrictions have been reported as a result of harmful wastes, such as drilling fluids and produced water generated during exploration, oil production, refining, transportation, and storage [2]. The effluent water from these processes consists of many organic hydrocarbons, such as aliphatic (n-alkanes), aromatic (toluene), and aromatic polycyclic (naphthalene), which are toxic and threaten ecosystems [3]. Furthermore, most of these components are non-biodegradable in wastewater, leading to environmental and health damages to all living and non-living organisms [4 - 5].

Produced water (PW) is formed during injection into the reservoir and naturally in a reservoir. Generally, it contains a high concentration of salinity, organic (hydrocarbon) and inorganic (cations and anions) compounds, toxic components such as heavy metals, and other ingredients [6]. Most of these components resulted from the oil extraction processes, and the others due to additive chemicals like corrosion inhibitors during oil production. The quality of PW depends on the geochemistry of the product, hydrocarbon types, well characteristics, and extraction methods. Therefore, the characteristics and volume of PW vary from one site to another. In addition, over time, the difference is also related to well age progress [7]. The vast quantities of PW led to the desire to recycle it through re-injection to increase petroleum production and reuse it for various industrial uses such as power plants, irrigation, and fire control. These uses have attracted many researchers to describe the physical and chemical treatment techniques of PW in several works [6, 8-10]. However, despite their efficiency, physio-chemical techniques such as chemical oxidation, adsorption, and membrane filtration have challenges in terms of lowering economic cost, amount of energy consumed, performance efficiency, and effects on the environment. The performance efficiency of these techniques

depends on several variables; the type of hydrocarbon, type of reservoir, salinity, conditions (temperature and pressure), viscosity, and speed of up-flow [6].

Bio-treatments have a history in remediation of industrial wastewater attributed to their ability to reduce chemical oxygen demand, heavy metals (e.g., cadmium), and trace organic pollutants, and the removal of specific pollutants, like arsenic present in a high concentration in some groundwater [11-12]. Bio-treatment can degrade organic compounds under the utmost temperature, pH, and salinity conditions Little informat. However, little is presented on the bio-tre. Therefore, this review will highlight the main PW bio-treatment technologies and include the challenges of environmental factors related to PW. Moreover, future research directions are also addressed.

2. Produced Water Origin

The various underground fluids like hydrocarbon (oil and gas) or saltwater are trapped in the subsurface-formed rocks. The process of trapping the hydrocarbons in the rocks is made after they are saturated with salt water, as the low density of the hydrocarbons causes them to migrate to trapped sites and displace some saltwater from the composition. In general, the rocks tend to absorb hydrocarbon and saline water [13,6]. Therefore, hydrocarbon is produced from the reservoir by injection of water to maintain the pressure inside the reservoir. However, in addition to injected water into the reservoir, natural water called formation water is always present together with hydrocarbon in sits below the hydrocarbons zone within porous reservoir media (Figure 1). Mixing water with hydrocarbons produces what is known as produced water (PW) [13-17]. Therefore, physical operations are carried out to separate hydrocarbon from produced water, such as phase separation and floatation [17].

PW associated with oil production usually has an approximate ratio of 3:1 PW: oil, and this ratio increases with continued gas and oil production and the age of the reservoir. Thus, managing these huge amounts is an issue that attracts the interest of researchers [18]. Therefore, produced water can be classified according to its origin into oil PW, gas PW, and Coal Bed Methane (CBM) PW [16].

2.1 PW From Oil Fields

The PW from oil reservoirs represents the largest source of environmental pollution in petroleum activities due to its containment of some hydrocarbon compounds. Most of these compounds can dissolve in water, such as aromatic compounds such as benzene, crayons, xylene, and toxic heavy metals (e.g., cadmium). Removal of these compounds is very difficult due to their toxicity [19]. Generally, the quantity of PW is low at the start of petroleum production. Still, it increases several times greater than the amount of hydrocarbon with the progressing age of the oil reservoir due to the decay of the oil production [20]. The produced water quantity and the life of a well depend on several factors such as the well drilling method (horizontal or vertical well), types of the reservoir (homogeneous or heterogeneous), various types of completion, techniques used for water separation, water injection or water flooding to enhance oil recovery, mechanical problems, and underground problems near the reservoirs [21-22].

2.2 PW From the Gas Field.

In gas fields, water injection is not used, so the produced water comes from formation water and condensed water. Therefore, the quantity of PW from gas fields is minimal with high toxicity compared with oilfield-produced water due to the acidic gasses dissolved CO_2 and H_2S [17]. In addition, when comparing the components of organic and inorganic compounds, salinity, and other components in Tables 1 and 2, their concentrations are higher in gas fields than in oil fields. In addition to the use of various chemicals during gas treatment, such as methanol and ethylene glycol as hydrate inhibitors to prevent the formation of gas hydrates, one-third of these components are retained in the PW, and the concentrations of volatile components are higher than those in PW of oilfields [23].

2.3 Coal Bed Methane.

It is considered a non-traditional source trapped in underground coal seams due to chemical and biogenic reactions. It is generated at a certain temperature and pressure conditions ($27\text{-}52^\circ\text{C}$ and 0.43 psi/ft to $<0.05\text{ psi/ft}$) through the bituminization phase, where methane gas is released. The increase of gas volume depends on the coal type, reservoir depth and pressure, and high surface area of coal volume [24].

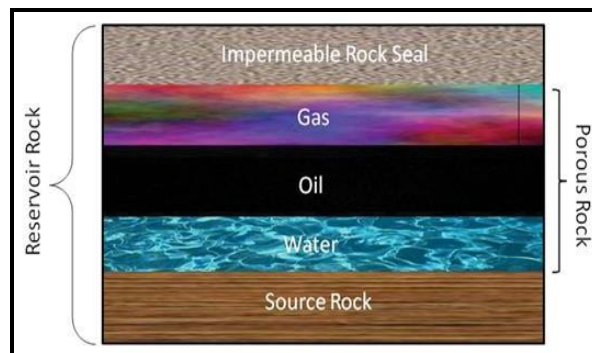


Figure 1: Design of a typical reservoir [16]

3. Ingredients of PW

PW has complicated compositions, so its physical and chemical properties are inconsistent. These properties depend on the field site, geological formation, extraction method, hydrocarbon type (oil or gas), and reservoir age [25]. The main constituents of PW are total dissolved solids (TDS), oil and grease (O&G), aromatic hydrocarbon (e.g., benzene, toluene, and xylenes), polyaromatic hydrocarbons (e.g., naphthalene), organic acids (e.g., acetic acid), phenol, inorganic component (includes anions and cations), heavy metals (e.g., nickel), radioactive materials (e.g., barium), and the chemical additives utilized in drilling, fracturing, and operation of the well [20,26-27].

The O&G contents are represented by the number of hydrocarbons present in the PW. Their quantities vary from country to country. The separation of O&G contents is difficult from PW at a low concentration under light and high temperatures [28]. In addition, PW also contains inorganic components (cations and anions) that contribute to its salinity, such as K⁺, Na⁺, Ca⁺², Mg⁺², Ba⁺², Sr⁺², Cl⁻, SO₄⁻², and SO₃⁻² [29]. Table 1 and 2 summarizes some of the ingredients of PW in gas and oilfields. The concentrations of cations and anions in PW are in ppm and differ from one reservoir to another and may reach 250,000 ppm of salinity. The concentration of salinity must be considered during bio-treatment because high salinity concentrations of salinity inhibit biodegradation, which leads to decreased biomass-respiration rate [30].

Table 1: The main ingredients of PW in the gas field [31-33]

Ingredients	Value in ppm	Ingredients	Value in ppm	Ingredients	Value in ppm
pH	(3.1 – 6.47)	Bromide	(150 – 1149)	Lead	< (0.2 - 10.2)
TDS	(139,000- 360,000)	Potassium	(149 - 3870)	Iron	(39 – 680)
TSS	(8 - 5484)	Sodium	(37,500- 120,000)	Zinc	(<0.02 - 5)
BOD	(75 - 2870)	Silver	(0.047 - 7)	TOC	(67 - 38,000)
COD	(2600- 120,000)	Barium	(9.65 – 1740)	Oil/grease	(2.3 - 38.8)
Copper	< (0.02 - 5)	Cadmium	< (0.02 1.21)	Benzene	(1.8 - 6.9)
Magnesium	(1300-3900)	Nickel	< (0.08 - 9.2)	Toluene	(0.857 - 3.37)
Calcium	(9400-51,300)	Chloride	(81,500- 167,448)	Surfactants	(0.08 - 1200)

Table 2: The main ingredients of PW in oil field

Ingredients	Value in ppm	Ingredients	Value in ppm	Ingredients	Value in ppm
pH	(4.3-10), (7.30 ±0.21) ^e	Copper	(0.04) ^f	Toluene	(0.058-5.86) ^{h, g}
Calcium	90 ^a , 72 ^b , 2 ^c , 165 ^d , (4247 ± 752) ^e , (0-74000) ^g	Cadmium	<0.001 ^b	Ethyle benzene	(0.086-0.57) ^{h, g}
Bromide	40 ^a , 16 ^b	Iron	1 ^b , (11 ± 9) ^e	Benzene	(0.032-14.97) ^{h, g}
Sodium	4240 ^a , 2976 ^b , 2976 ^c , (42,720 ± 2093) ^e , (0-150000) ^g	Nickel	0.018 ^b , 0.01 ^f , (0.02 ± 0.004) ^e	Xylene	(0.553-2.69) ^h
Barium	1 ^b , (1.0 ± 0.0) ^e , (0 - 850) ^g	Zinc	1.74 ^b	BTX	(0.39 – 35) ^g , (0.73- 24.1) ^h
Chloride	5290 ^a , 3861 ^b , 717 ^c , (65,800 ± 1600) ^e , (0 - 250000) ^g	Mercury	<0.01 ^b , 0.83 ^f	PAH	(0.005 - 0.129) ^h
Sulfate	204 ^b , 36 ^d , (1010 ± 9) ^e , (0-15000) ^g	Lead	0.002–8.8 ^h	Phenol	(0.009 – 23) ^g
Magnesium	9 ^a , 34 ^b , 1 ^c , 25 ^d , 727 ± 54 ^e , (98- 6000) ^g	TDS	10460 ^a , 8367 ^b , 5090 ^d , (100 - 400000) ^g	COD	1220

[34]^a, [35]^b, [36]^c, [37]^d, [38]^e, [39]^f [40]^g, [14,41]^h

4. On-site Treatment of PW

The generated PW from the onshore oil industry is often used worldwide for many purposes, such as re-injection into the soil to improve oil recovery and for other industrial uses. Onshore oil and gas processors are designed to remove the O&G content and solid suspension to avoid pump plugging and damage. While in offshore processes, the treated PW is discharged to the sea after reducing the concentration of O&G to 30-40 ppm to minimize the toxicity impact on aquatic life [26, 42].

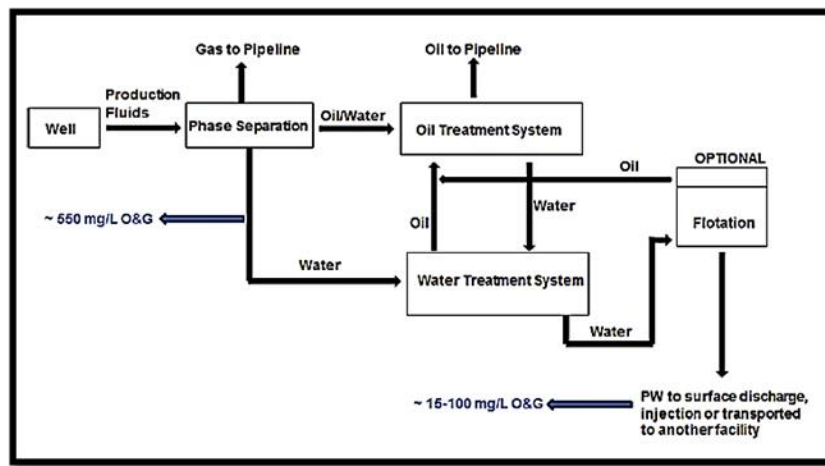


Figure 2: On-site treatment units of PW [43]

The crude oil stream is dewatered in process steps in petroleum process activities. The separation unit consists of two or three stages. Each stage contains two output streams, the first is rich in hydrocarbon that will be purified in the oil treatment system, and the second is the gas stream, as shown in Figure 2. The water extracted from the two phases follows primary and secondary treatments: water treatment system and floatation, respectively. However, the outflow from this traditional treatment is not acceptable with the criteria for reuse in agriculture or industrial uses in most cases [42- 43].

As long as the volume of PW exceeds several times, the hydrocarbon production of approximately 250 million BPD of PW to about 80 million BPD of oil depends on the ratio of 3:1 PW: oil, so it is necessary to treat the PW for environmental and operational reasons [20]. Several treatments were used to manage PW, including physical, chemical, and biological combinations between them. These treatments include different techniques applied in the petroleum industry to eliminate the organic and inorganic components. Among these techniques, ion exchange [44], electrocoagulation [45], membrane filtration [46], photocatalysis [47], adsorption [48-50], and bio-treatment utilizing microorganisms are widely used [2, 5, 11]. The bio-treatments are one of the most important technologies that receive great attention from the researcher's point of view due to their ability to degrade organic compounds under extreme conditions, in addition to being cost-effective and environmentally friendly. Therefore, this review will describe the main bio-treatment technologies applied to treat PW from pollutants.

5. Bio-Treatment

Microbial biodegradation is known to be an effective bioremediation for the disposal of various types of compounds, such as organic in PW. It degrades contaminants by utilizing the metabolism of microorganisms to degrade a wide range of organic components. So, bio-treatment of wastewater is a growing and efficient technique for removing various contaminants [51]. The main advantage of bio-treatments is that they are economical compared to conventional treatments due to their low operating cost, which ranges from 0.10 to 0.30 €/m³ [41]. Besides being inexpensive, these treatments do not affect the ecosystem. So it deems a suitable solution to remove contaminants. Moreover, a biological treatment can treat low concentrations of pollutants, while physical and chemical treatments cannot remove them. Unfortunately, the application of biological techniques is still restricted by the need for prolonged and unpredictable decomposition in the long term [6]. Bio-treatment is applied in aerobic and anaerobic conditions for industrial effluent by various microorganisms [52-54].

Four sources of microorganisms were utilized in these processes: naturally microorganisms (e.g., bacteria), commercial microorganisms (e.g., yeast; utilized by humans to produce foods), specific groups of microorganisms (groups of microbial cells such as viruses and fungi), and adapt sewage sludge (bio-solid) [55]. In aerobic degradation, some pollutants are a source of carbon and energy for microorganisms that can produce decomposition enzymes. Monoxygenases and Dioxygenases are the main enzymes that stimulate reactions by incorporating oxygen into the structures. Under anaerobic digestion, microorganisms can perform the oxidation of substrates by transmitting electrons to the appropriate acceptors. A general microbes degradation of organic materials as shown in Figure 3. The oxidation can be carried out in various respiration pathways.

- 1- Denitrification; many aerobic and anaerobic bacteria can decrease nitrate to molecular nitrogen.
- 2- Sulfate Respiration; sulfate-reducing bacteria can eliminate sulfate to hydrogen sulfide and mineralized BTEX.
- 3- Iron and Manganese Respiration; Fe³⁺ and Mn⁴⁺ are eliminated to Mn²⁺ or Fe²⁺.
- 4- Acetogenesis and Methanogenesis; CO₂ is eliminated from acetic acid or methane biogas, resulting in reduced chemicals.
- 5- Fermentation; organic compounds are oxidized, and their intermediate compounds act as an electron acceptor [54,56].

Under both aerobic and anaerobic conditions, oxidation includes electron transfer between donor and acceptor in the respiration chain. A proton transfer across a membrane leads to the production of adenosine triphosphate (ATP) and Nicotinamide adenine dinucleotide phosphate (NADPH₂) as an energy source for living cells' growth and other reactions that require energy [54].

Accordingly, bio-treatment operations appear as a suitable solution due to their high degradation efficiency of elements and low running cost and being eco-friendly [36,57]. Therefore, the main technologies utilized for bio-treatment (aerobic and anaerobic conditions) of real and synthetic PW will be summarized below.

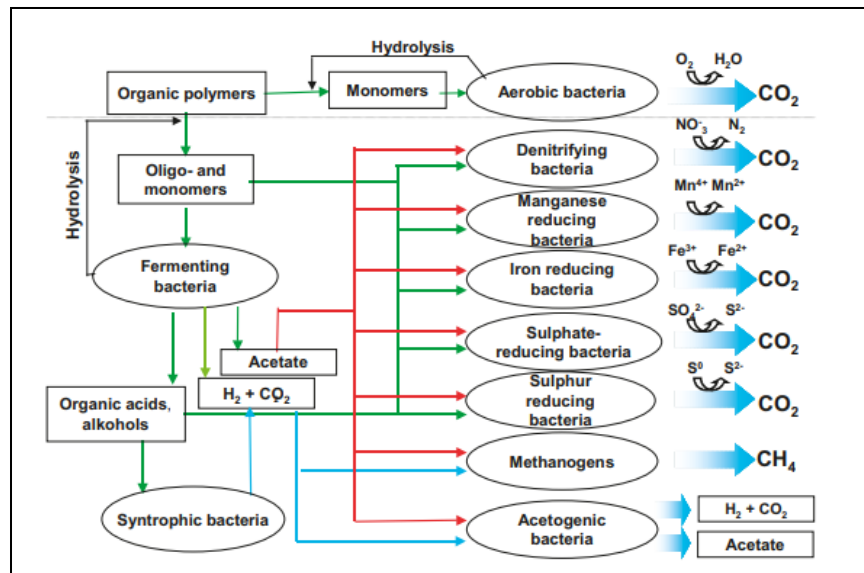


Figure 3: Aerobic and anaerobic decomposition of organic materials [54]

5.1 Aerobic Conditions

5.1.1 Activated Sludge

Activated sludge is the most common biologically effluent treatment method. It consists of an aerated tank for mixing the biomass of microorganisms with the polluted water, followed by a sedimentation unit to separate the sludge from the treated water [13].

Activated sludge includes conventional activated sludge and series batch reactors (SBR). Conventional activated sludge (CAS) treatment is a good technique because it is economical, has little environmental impact compared to other treatment techniques, and effectively removes chemical demand for oxygen and other pollutants [13,6]. Moreover, it is an effective total petroleum hydrocarbon (TPH) removal technology where 99% removal efficiency of TPH was obtained in 20 days of solids retention time (SRT) [55].

Conventional activated sludge was characterized by different parameters including biological loading rate in (kg COD/ kg MLVSS/ d), MLVSS (mixed liquor volatile suspended solid), organic loading rate in (kg COD/ m³/d), hydraulic rotation time (hr), and the sludge retention in (day) [41]. It is effective in industrial wastewater treatment as some studies have recorded using CAS with PW. Tellez et al. [55] studied the activated treatment of real PW at salinity 35 ppm, 0.86 kg COD/m³/d organic loading rate for 12 hr HRT. Their results showed that the COD removal efficiency reached 98% due to microorganisms' acclimation for 10 days. In contrast, E. Kardena et al. [58] showed that (80.7% and 82.4%) removal efficiency of COD was obtained at (25 d and 20 d) of SRTs and 20 hrs of HRT for synthetic PW in CAS, as illustrated in Figure 4.

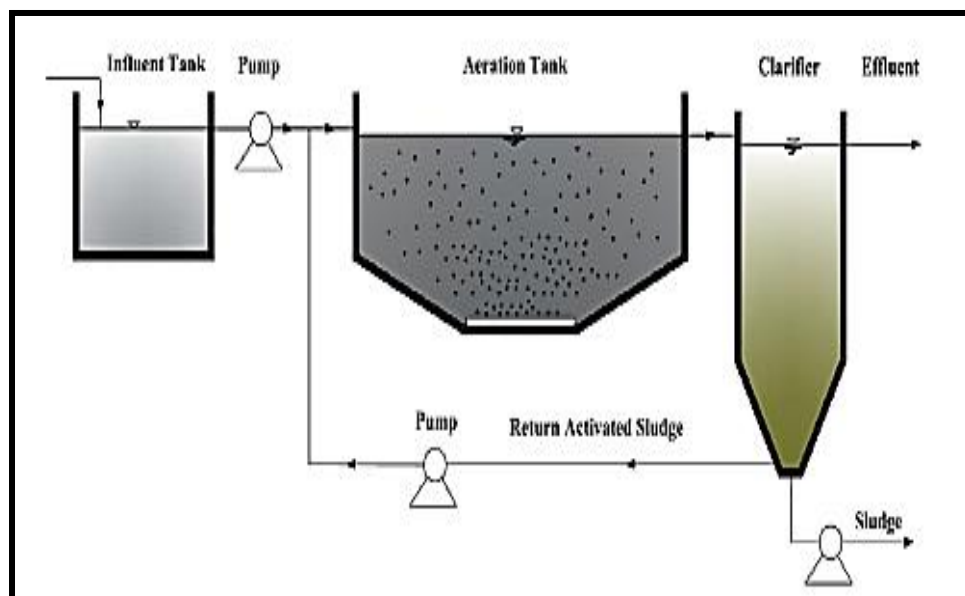


Figure 4: The diagram of bio-treatment using activated sludge [58]

Sequencing batch reactors (SBRs) are the same as conventional activated sludge treatment but have the benefits of a smaller footprint due to a separate clarifier. For example, Freire et al. [59] found that 30% to 50% removal efficiency of COD was obtained by diluted acclimated sewage sludge in SBR with various proportions of (45% and 35% (v/v) domestic PW. On the other hand, the optimal removal of total organic carbon (TOC) from PW with acclimated microbes in 180 ppm NaCl was observed in SBR after using three bio-treatments units such as inclusive SBR chemo state reactors and trickling filters [58].

Pendashteh et al. [57] studied SBR treatment of synthetic and real PW at different concentrations of TDS in which NaCl was added to increase the TDS and concluded that COD removal in synthetic (> 90%) was higher than in real (81%). Freire et al. [59] found that the salinity had no efficacy in removing COD when diluted with mixed wastewater, while the organic components affected the bio-treatment. Wei et al. [60] proved that when the concentration of Cl⁻ was increased from 2000 to 36000 ppm, the inhibitory impact of the high salinity on combined microbial growth was measly. As salinity increases more than or equal to 100,000 ppm, the biodegradation rate decreases, resulting in environmental stress [61]. Other studies related to the use of activated sludge in the sequencing batch reactors (SBR) process with various parameters are shown in Table 3.

Table 3: Previous studies of producing water treatment using activated sludge in sequencing batch reactors (SBR) process

Type of stream	TDS ppm	COD ppm	Operation condition	Results	Ref.
Real oil field	52,100	2000	24 h, for 1 cycle time, and dilution with different percentage (10–45% v/v) of domestic wastewater.	Removal efficiency: 30–50% COD, 95% ammonium, and 65% for phenol	[59]
Synthetic	152,000	-	12 h for 1 cycle time	99.5% removal efficiency of phenol	[62]
Real oil field	22500	1218	HRT for 6 h and 8 h cycle time	50% removal of DOC	[63]
Real oilfields	220,000	399 and 130 of TOC	0.33m ³ /m ³ day, inoculum acclimated microorganisms	80% removal of TOC	[64]

5.1.2 Membrane Bioreactors (MBR)

Membrane bioreactors (MBRs) have been widely employed and are the most common treatment technique. This is because MBRs are a good filter for PW treatment and the sludge settling is unnecessary because the membranes are utilized to separate solids. So, the outer clarifiers are not used. Thus, it has a light spot compared with other categories of bio-treatments techniques [11]. There are two major categories of MBR depending on the site of the membrane unit in operation, as shown in Figure 5. When it is inside the aeration tank, it is called immersed MBR, and if the membrane module is outside the aeration tank, it is called external. In general, the objective of installing the membrane unit outside the aeration tank is to reduce the operational cost resulting from the air supply to reduce pollution [65].

MBRs have two sorts of membrane–filtration based on the nature of stream flow on the surface of the membrane and the aggregation of suspended solids on the surface, resulting in the cake layer formation. Membranes are usually made of ceramic or polymeric materials. Ceramic membranes are preferred over polymeric membranes for ease of cleaning and high chemical resistance, although polymeric membranes are easy to prepare and inexpensive. So, the main challenge is from an economic point of view for those membranes [66]. Table 4 reviewed some previous studies where the relevant data showed that the COD removal efficiency was more than 80%, with the difference in the process parameters that determine the treatment efficiency.

Table 4: Previous studies of treating PW using Membrane Bioreactors (MBRs)

Type of influent	Salinity TDS ppm	COD ppm	Operation conditions	Results	Ref.
Synthesis and real	different concentration of NaCl from (35,000, - 250,000), and 1640 real	1240	HRT from 8 to 44 h, 12–48 h cycle Time, for 0.62 kgCOD/ m ³ d for OLR	> 90 % removal efficiency of COD	[39]
Real oilfields	8367	2371	SRT for 30 days, flux = 10L /m ² h ¹	Removal over 80% of COD and 99% removal of TPH	[35]
Synthesis	35000	2250	HRT for 48 h, 80 L/ m ² h ¹ OfHLR, 22.5–23.5 h for cycle time, at 30 °C	Mg, Al, Ca, Na, K, Fe, rod-shaped bacteria in pollutants, contributed	[57]
Synthesis	64400	Different value (600, 1200, 1800)	48 h of HR, SRT for 80 day, and with different OLR (0.3, 0.6, 0.9) kg COD /m ³ d	More than 80% removal of COD	[67]
Real oilfields	5189	1222	HRT range from 6 -32 hr, 60–120 day of SRT, at 22–38°C, and the flux range from 3–15 L m ⁻² h ⁻¹	More than 90 % removal of TPH, and 60% removal of COD	[68]

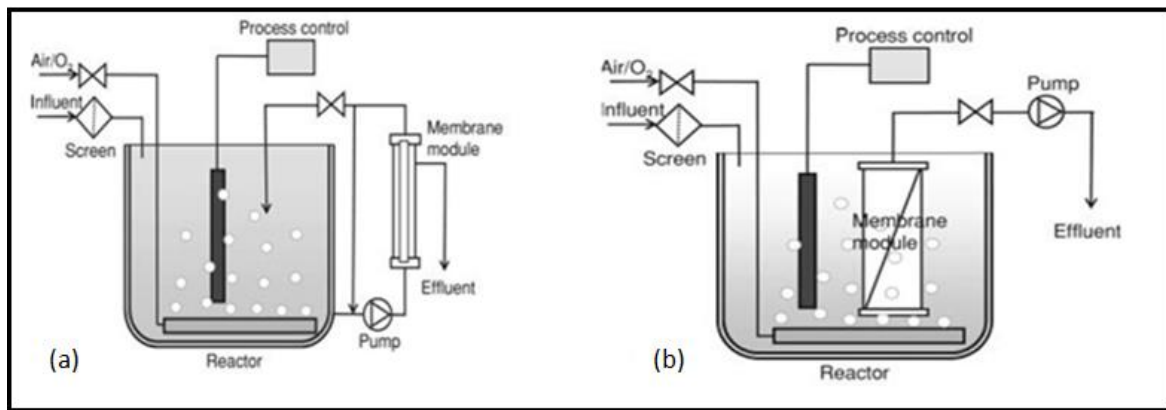


Figure 5: Membrane Bioreactors sort (a) External (b) Immersed [69].

5.1.3 Fluidized Bed Bioreactors (FBBs)

FBB is a kind of aerobic biological technique in industrial wastewater treatment and has proven effective in treatment. The process is performed by fixing the biomass onto the fluidized bed particles and liquid flowing up [70]. The particles are smaller than those used in the MBR technique, which is attributed to the thicker biofilms. Therefore, FBBs have been shown to withstand large loads and operate at lower HRT values compared to a typical bioreactor. The main benefits of this technique are a large biofilm–liquid interfacial area, increased concentration of immobilized microorganisms, and enhanced mass transfer [71]. Different categories of fluidized bed bioreactors (FBB) are shown in Figure 6. This technique is employed for hydrocarbons wastewater in three phases (gas–liquid–solid). The inoculum is the refinery-activated sludge that is inoculated onto polypropylene particles and fluidized by upward airflow [2].

FBB is an efficient technique for removing hydrocarbons from wastewater. Still, it is often inhibited by some limitations, such as mass transfer among three phases of aqueous hydrocarbons and the particles with biomass. Therefore, the particle must have the optimum size in the carrier, and the density must be smoothly fluidized to absorb the organic components from the stream. In addition, the living cells must be resistant to damage [72].

Kuyukina et al. [73] evaluated the performance of an FBB technique using immobilized *Rhodococcus* cultures with sawdust to remove organic components from an oilfield PW containing 10300 ppm of COD and 3740 ppm of TPH. The results indicated that 70% biodegradation for saturated hydrocarbon and PAHs was obtained over two weeks. They also found that 75–96% removal efficiency of heavy metals was gained due to the combined effects of biodegradable biomass and physical adsorption by sawdust. While Serebrennikova et al. [74] found that lower performance of FBB was recognized for real oilfields, PW of high TDS in which *Rhodococcus* encapsulated with granules of polyvinyl alcohol was used due to the encapsulated cells have greater resistance to high TDS and organic components.

5.1.4 The Biological Aerated Filter (BAF)

Recently, BAF technology has been widely used as it can remove complex and poorly biodegradable components. In this system, living cells are fixed in the bedding substance, and effluent flows through a fixed bed. The packing matter includes natural materials such as charcoal, wood, and activated charcoal, as well as synthetic materials [34, 41]. BAF is a kind of immobilization reactor that can keep the hydraulic loading rates up and maintain a high biomass concentration to reduce environmental shocks. Thus, it leads to the minimal formation of waste (sludge) and promotes the growth of living cells [75]. Therefore, BAF is an efficient bio-treatment since it uses microorganisms together with a bioreactor, which enhances COD degradation to more than 85% and 100% for benzene [76]. Zahao et al. [76] showed that 75-90% oil/grease and 78% total organic carbon was removed from real PW from the oil field where a specific group of microorganisms was used that was a suitable system for treating real PW. Freedom et al. [34] investigated lab-scale BAF where packing of activated carbon was used to treat PW and found that 28% dissolved organic carbon was removed due to its adsorption on the surface of packing matter. In comparison, the removal efficiency increased to more than 90% at 60 hrs of HRT when combined with microorganisms. Riley et al. [77] reported that 72.4% removal efficiency of PW organic compounds (petroleum-field) was obtained using BAF with microorganisms at 3.7 hrs of HRT and 0.55 OLD ($\text{Kg COD/m}^3\text{d}^{-1}$).

5.1.5 Aeration Lagoons

Aeration lagoons are deep from 3-4 meters, oxygen is fed by aerators and not by photosynthetic algae, suspended biomass is maintained, and dissolved oxygen is provided, allowing the maximum aerobic activity. The bubble aeration is from compressed air pumped into plastic tubes at the bottom of the lake base. Aeration lakes are effective in treating biodegradable wastewater as industrial water. The hydraulic retention time (HRT) is 3-8 days depending on the wastewater temperature, degree of treatment, and strength. Generally, 5 days of HRT at 20 °C results in 85% BOD removal efficiency in household wastewater, while if the temperature drops around 10 °C, the BOD removal drops to 65% [78]. Peitz and Xavier [79] studied the aerated lagoon modified with sponge support media (APG) to treat the industrial effluent by removing 50% COD, 75% BOD, and 20%, 18% color and total phenolic, respectively, at 1.2 $\text{kg COD m}^{-3} \text{d}^{-1}$ of organic load rate (OLR).

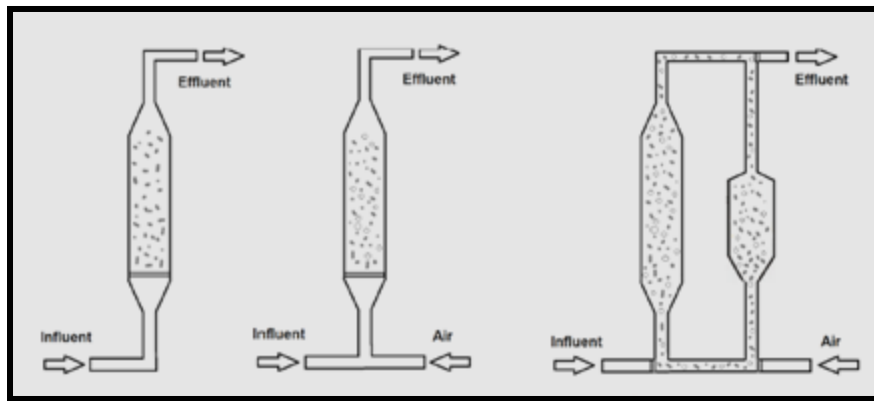


Figure 6: Types of Fluidized Bed Bioreactors (FBB) [2]

5.2 Pros and Cons of Aerobic Treatment Technologies for PW

In general, aerobic treatment is fast and effective for eliminating degradable pollutants. The major trends and differences in aerobic techniques depend on environmental factors' challenges and the sort of microbial cells. An appropriate selection of aerobic treatment should meet specific demands of practical situations, which can effectively treat large amounts of PW. Table 5 summarizes some features of aerobic techniques as the pros and cons of aerobic treatment technologies are described.

Table 5: Features of aerobic treatment techniques

Technology	Pros	Cons	Ref.
Activated Sludge	<ul style="list-style-type: none"> -It produces high-quality water while remaining active sludge. -It does not require much space to install and run the system. -Safe and easy operation. -The process is relatively effective. 	<ul style="list-style-type: none"> -Problems with any changes in the type or volume of sewage -Costs increase over time (aeration costs and sludge recycling). -It requires confirmation that the sludge remains active. 	[13,6]
Membrane Bioreactors (MBR)	<ul style="list-style-type: none"> -High-quality water suitable for water reuse -High volumetric load is possible -High rate of biodegradation 	<ul style="list-style-type: none"> -Compression of sludge into external MBR -Membrane contamination. -High cost. 	[11, 65,66]
Fluidized Bed Bioreactors (FBBs)	<ul style="list-style-type: none"> -Easy to control operation. -High mass and heat transfer between the gas phase and the solid surface. -Fast mixing results in swift changes in control, making it safer. 	<ul style="list-style-type: none"> -Mass transfer among three phases. -Possibility of damaging microbial cells. -Energy consumption. 	[2, 71,72]
The Biological Aerated Filter (BAF)	<ul style="list-style-type: none"> -Elimination of secondary refineries reduces additional costs and operational problems -The low space requirement is due to the small footprint. -Automated process. -It can deal with changing flow rate and temperature in addition to being effective with dilute polluted water. 	<ul style="list-style-type: none"> -Adequate training of automatic control system operators. -Requires preventative maintenance. -Relatively high cost compared to activated sludge technology 	[34,41, 75]
Aeration Lagoons	<ul style="list-style-type: none"> -The aerated lagoons are simple and effective. -Aerated lagoons demand 5-10% of the land area as ponds. -The aerated lagoons are frequently applied for the bioremediation of industrial effluents. 	<ul style="list-style-type: none"> -Problem in cold weather. -Inefficient in deep water. -Inefficient aeration. -Maintenance required. 	[78,79]

5.3 Anaerobic Conditions

Although aerobic treatment has effective results in removing organic components that have the potential to biodegrade, the challenges of aerobic treatment are expensive due to the high operating cost and result in the production of another type of waste (sludge). In contrast, anaerobic treatment was chosen because it is effective, inexpensive, and eco-friendly [78,80]. Additionally, through anaerobic treatment, methane-rich biogas is produced for on-site use for mechanical and electrical power. Thus, anaerobic treatment was considered a preferential treatment [81].

Anaerobic digestion is a complex process that takes multiple steps, in which organic compounds are degraded into basic ingredients and methane in the absence of oxygen[82]. Figure 7 shows the metabolic pathway of anaerobic digestion associated with the presence of microbial assemblies [83]. However, anaerobic digestion can be utilized in treating PW where high salinity leads to inhibition and toxicity problems at the methanogens step. The degree of inhibition depends on the sodium ion concentration [84]. McCarty [85] verified that sodium is the basis for the methanogens step at a limited concentration of (100-200) ppm. But with increasing concentration (3500 - 5500) ppm, it would be moderately inhibited, and over 8000 ppm, it is strongly inhibited by methanogens. The high salinity concentration in PW affects the metabolism of microorganisms as the salt leads to plasmolysis. The increase in salt concentration in the digester is attributed to using a basic solution like NaOH or Na₂CO₃ to adjust the pH value. Therefore, sequential dilution of inhibitory matters or blending methods is recommended to remove toxicants [86,87].

Ghorbanian et al. [81] found that more than 98% removal of TPH was obtained in an anaerobic UASB with fixed-film media and in an anaerobic SBR [80]. F. C. Khong et al. [88] proved that increased removal efficiency of COD by diluting the

treated PW can be obtained. In another study, Hua et al. [89] obtained 74% COD removal as a result of both anaerobic and aerobic treatment and >90% removal of ammonia with the change in HRT from 12 hs to more than 10 days in anaerobic treatment. Ji et al. [90] noted that 65% removal of COD and 88% heavy oil removal from oilfields PW can be acquired under conditions of high salinity, $0.20 \text{ kg CODm}^{-3} \text{ d}^{-1}$ organic loading rate, and 2.5 days of HRT.

Anaerobic treatment is an accurately balanced ecological system in which special groups of organisms degrade biomass in the absence of oxygen in both natural and engineered systems. It is one of the oldest biotechnologies used to provide clean energy from organic waste to avoid the destructive effects on the environment from the energy generated by the combustion of petroleum. Therefore, anaerobic treatment is one of the approaches to a circular bio-economy [80]. Biogas composition depends on the redox state and biodegradability of organic waste. It is mainly composed of methane, carbon dioxide, water, and nitrogen and contains hydrogen sulfide, ammonia, and oxygen [82,83]. The number of biogas plants worldwide is expected to exceed 1,000 in 2020, of which only 729 are in Europe, with Germany having the largest number of biomethane plants, followed by the United Kingdom and Sweden [91].

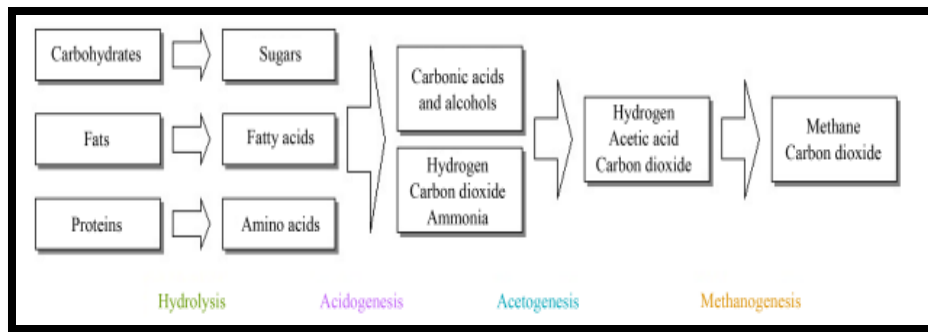


Figure 7: The main steps of anaerobic treatment[83].

6. Challenges of Environmental Factors

The most significant bioenvironmental factors are temperature, pH, dissolved oxygen, the concentration of nutrients, and toxic substances. These factors can be controlled in a bio-treatment process to ensure that microbial growth is preserved in optimal conditions [92-93].

Bio-treatment processes are usually performed for wastewater in the mesophilic temperature range of 20°C to 40°C using aeration tanks and percolating filters run at a range of 12°C to 25°C . Therefore, the ventilation rate is responsible for heat loss. In contrast, increasing the temperature leads to an increase in the growth and metabolism of bacteria. This leads to an increase in the efficiency of removing organic or inorganic pollutants [94]. Lu et al. [86] studied the effect of temperature in the treatment of real PW (Shengli Oilfield), where the outflow temperature was 55°C . In contrast, the environment temperature during the study ranged from $(-15$ to $-5^{\circ}\text{C})$ and noted that the environment temperature is the biggest challenge for bio-treatment. Al-Zuhairi et al. [5] improved biogas production of anaerobic co-digestion from municipal solid wastes using lignocellulosic materials under mesophilic conditions (37°C).

The pH or acidity in the aquatic environment affects the removal of organic pollutants from wastewater through their effect on the microorganisms' physiology and the pollutants' solubility in the wastewater. So, acidity is one of the key impacts affecting the decomposition of organic substrates. Better removal of pollutants from wastewater can be carried out under acidic conditions, which is attributed to the protonation state affecting degradation and sorption processes. Therefore, industrial wastewater can be treated at lower pH to raise the rates of biodegradation, and the change in the pH value can be controlled to prevent further pollution [95,96]. The provision of dissolved oxygen is one of the important points for aeration in bio-treatment. Ai et al. [97] measured the flow velocity and dissolved oxygen (DO) in MPSR (Micro-Pressure Swirl Reactor) at a stable circular circle flow using a $0.2 \text{ m}^3/\text{h}$ aeration rate due to improved removal of nitrogen and phosphorus.

Salinity is one of the factors that contribute to toxicity, and that has a negative impact on the environment. Sodium is the main dissolved component in PW, degrading the soils, which may change the clay and soil textures. Therefore, salinity affects soil and water quality by inhibiting bio-treatment processes. The efficiency of these processes depends on the COD reduction associated with total dissolved solids (TDS) concentration and is inhibited more in real PW than in synthetic PW [98]. Pendashteh et al. [57] obtained more than 90% removal of COD when TDS was 35,000 ppm in synthetic PW, while 74 % of COD was removed when TDS was 250,000 ppm. Pendashteh et al. [99] also studied the variation between real and synthetic PW in bio-treatment, where 90% COD removal in the synthetic PW was obtained. In comparison, 18% removal of COD was observed in real PW when TDS was 250,000 ppm. Kekacs et al. [100] investigated the effects of salinity on aerobic degradation and found that TDS greater than 40,000 ppm inhibited microbial growth on the pilot-scale.

7. Future Research Directions

Bio-treatment technologies have proven to be highly efficient in treating PW. However, the future research direction of treating PW requires recognition of PW as an important strategic resource in the industry and its importance in many other uses. Therefore, it is necessary to develop an appropriate management strategy for PW treatment to avoid environmental impact and/or reuse it for the sustainability of the hydrocarbon production sector. Recently, biotreatment techniques have been combined to enhance the performance of pollutant elimination, such as anaerobic digestion followed by aerobic treatment

[101]. On the other hand, aerobic granular sludge replaced activated sludge with better sedimentation capacity with a significant reduction in sludge volume and promises a sustainable treatment for the future [102]. Granular sludge is mainly utilized in sequencing batch reactor (SBR), which modifies the activated sludge treatment. The essential feature of the SBR method with granular sludge is the shorter time to obtain effective separation of activated sludge [103].

The development of new membranes requires anti-fouling properties while reducing the cost of using waste substances as feedstock. Also, investigations should be conducted to analyze and quantify the toxicity of the biodegradation output and to choose their application as value-added products [104]. Accordingly, a suitable membrane should be developed for its wide application in the water plant.

Future research should focus on pure culture development and mixed culture biotreatment techniques that lead to the optimization of microbial strains to enhance desired properties using genetic and metabolic engineering tools and methods [105, 106]. Also, immobilization of living cells on a micro surface has been increasingly studied recently to obtain a biocatalyst with high performance as an efficient approach for the treatment of oily wastewater [73,107,108]. Serebrennikova et al. [74] investigated the potential of an immobilized consortium of actinobacteria on a polymeric carrier for treating oilfield PW in a bioreactor. Moreover, biotechnology advances have extended to immobilizing organisms on the nano surface to attain nano-bio catalyst as an emerging technique [109]. Thus, the continuation of scientific research in developing these environmentally friendly technologies will expand their application, boosting future PW management and water preservation.

8. Conclusions

Oil and gas extraction is one of the most water-consuming industries due to the large amounts of water used in production and refining; thus, wastewater is generated. PW is the effluent associated with oil and gas extraction operations that are formed either during injection into the reservoir or naturally. It contains various organic, inorganic, and toxic compounds, while the amounts of PW vary from site to site and as a result of well age progress. Therefore, the generation of large amounts of PW led to the desire to recycle it by reducing its toxicity to avoid environmental impact. Bio-treatment technologies are recognized as one of the methods to reduce the toxicity of effluents from petroleum process activities, as they are used to remove or degrade pollutants in an environmentally friendly manner.

This review reviews the origin of PW, the main bio-treatment technologies, the challenges of environmental treatment factors and the future research directions. The bio-treatments at aerobic and anaerobic conditions are based on microbial assembly that can biodegrade organic components of PW. Moreover, bio-treatment technologies are effective techniques from an economic point of view that are inexpensive compared to conventional treatments for PW.

However, bio-treatment applications are still likely limited due to the working time to remove/degrade high-risk compounds and convert them to less serious ones. Therefore, efforts must be made by researchers to develop bio-treatment technologies that have the potential to degrade various pollutants in less working time.

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Author contribution

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare no conflicting interest regarding the authorship and publication of this paper.

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