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Research Article

Niger Delta Oilfields Produced Water Characteristics and Treatment Technologies: Challenges and Solutions

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Abstract

The Nigerian Niger Delta oilfields have high water-to-oil ratio ranging from 50% to 95% water content, due to its secondary and tertiary production phases. Oil and gas producers could shut-in such wells, or develop cost effective approach for Produced Water, PW handling to meet reinjection or environmental permissibility. Thus, the study investigated the compositions and treatment techniques of Niger Delta oil and gas fields PW, and proffered solutions for actualizing minimal hazardous contaminants in PW. Characterization of PW from a Flow Station, an Oil processing and a Gas processing facilities showed biogeochemical homogeneity in the PW compositions with high organic and inorganic constituents, which are above injection and disposal specifications. The results of treated PW from the extant PW treatment (PWT) techniques showed that the total dissolved solids (TDS) concentration (6105.9 mg/l) from the Flow Station PW treatment facility did not meet the required specifications for injection into depleted wells or disposal into the environment (2,000.00 mg/l for inland, and 5,000.00 mg/l for nearshore). The salinity contents in the treated PW from the three PWT configurations were 2411.0 mg/l, 2218.6 mg/l, and 2165.4 mg/l, respectively, which were slightly above Nigerian Upstream Petroleum Regulatory Commission (NUPRC) specification (2000.0 mg/l) for nearshore disposal. The chemical oxygen demand (COD) concentration in the treated PW from the three PWT configurations were 153.0 mg/l, 148.1 mg/l, and 141.2 mg/l, respectively, which were above the NUPRC standard (125.0 mg/l). The oil and grease (O&G) concentration in the treated PW were 84.7 mg/l, 51.5 mg/l, and 58.0 mg/l, respectively, which also were above regulatory stipulation (30.0 mg/l) for nearshore disposal. The modular Bio-Unit + Ultra/Nanofiltration achieved more than 95% removal of both organic and inorganic constituents in the PW. Therefore, this study suggests that reconfiguring the extant PW treatment equipment with this cost-effective innovation would be the solution to PW treatment challenges in the Niger Delta oil and gas operations.

Keywords

Biotreatment, Characterization, Ecofriendly, Innovations, Physicochemical, Produced Water

1. Introduction

Water pollution is a major global concern. The quality of water resource available for human, flora and fauna consumption is threatened by industrial and domestic activities. Large quantities of both household and industrial wastewaters devoid of proper and adequate detoxification are disposed into the ecosystem. The oil and gas industries generate vast volume of toxic wastewater during the exploration, production and processing of oil and gas. This toxic byproduct is called

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Produced Water (PW) and constitutes large percentage of waste stream that finds its way into the water bodies. PW refers to water from underground formation which is unavoidably taken to the surface when extracting crude oil or natural gas.

Petroleum hydrocarbons are found in porous layers of sedimentary rocks sandstones in the Nigerian Niger Delta region [1]. Fluids passes through these rocks through pores connectivity, which is overlapped with impermeable rock. It is hypothesized that utmost all oil-producing formations were wholly flooded with water referred to as formation or connate water, before hydrocarbon accumulation [2, 3]. Over time, the petroleum hydrocarbon drifted to locations where it is trapped, dislocating water in the formation to become a reservoir of gas, crude oil, and water mixture at equilibrium. Mining of petroleum hydrocarbon to the surface does not only bring the formation water to the surface, but also reduces pressure in the reservoir, thus extra water may be added to the reservoir as means of sustaining reservoir pressure and increasing productivity [4-6]. Also, chemicals are used during drilling and production operations to inhibit corrosion, emulsification, and scale formation. Therefore, PW is a composite of formation and injected waters, and extraction chemicals surfaced together with petroleum hydrocarbon [7-10].

PW constitutes the principal waste stream generated by petroleum operations. Studies have shown that oilfields contribute greater than 60% of produced water discharged globally and will increase as the oilfield ages [11]. While Fukhru'l-Razi et al. [4] divulged an estimated 3: 1 water/oil ratio, Bryce [12] estimated an average water/oil ratio of 4: 1 globally. Guerra et al. [13] reported that between 7-10 barrels (280-480 gallons) of water are generated for every barrel of crude oil, while the American Petroleum Institute (API) has valued water/oil ratio in conventional oil reservoirs to be about 9 barrels (378 gallons) per barrel of oil [14]. Tellez et al. [15] have reported that PW volume in an oilfield may be about eight times higher than oil produced. Though the volume of water produced from Nigerian oil and gas industries is not well documented, it was mentioned that with currently projected 1: 1 water/oil ratio, the volume of water disposed yearly through oil and gas activities is about one billion [16]. Some oil and gas production facilities in the Niger Delta generates ≥30,000 bpd PW, while producing about 430 mmscf/d of gas.

PW composition and physicochemical properties varies with oilfield locations and over time. The variation depends on several factors namely, the geological structure of the formation, reservoir characteristics and age, production chemicals, strategy and process and type of petroleum hydrocarbon produced [4, 17-19]. The Niger Delta oilfield PW composes of both organic and inorganic compounds having different concentrations of suspended and soluble petroleum hydrocarbons, naturally occurring radioactive materials, heavy metals, formation/produced solids, dissolved gases, scales, salts, microorganisms, and process chemicals [3, 5, 20-22]

Untreated or partially treated PW has adverse effects on human, environment, and oil/gas production facilities. PW has been found to denote more than 97% of oil dumped from offshore operations into the marine [23, 24] which makes it a major source of aquatic pollution. It has been reported that Niger Delta offshore seawater and sediments are polluted with benzene, toluene, ethylbenzene, xylene (BTEX), polycyclic aromatic hydrocarbons (PAH), alkyl phenols, anions, and cations from discharged PW [25, 26]. Farming and fishing activities, which are mostly the traditional mainstay of Niger Delta indigenes, have been disrupted and dislocated due to pollution resulting from deposed of inadmissible PW into the environment [27]. It has also caused decline in crop yields and migration of aquatic animals away from their natural habitats.

Studies have associated PAH and phenols dissolved in PW with health issues such as biochemical stimulation, non-polar narcosis, phototoxicity, which triggers carcinogenicity, mutagenicity, teratogenicity, hematological, genotoxic, immunotoxic, and carcinogenic, endocrine disorder [24, 28-30]. Untreated PW causes high chemical oxygen demands (COD), high salinity and heavy metals in the receiving water bodies. COD reflects the amount of oxygen consumed for chemical breakdown of organic and inorganic matter. PW with high COD depletes oxygen in the receiving water bodies and negatively impacts the biota. Sodium, a major cation in PW, in high concentration competes with other cations for assimilation by flora, thus causing deficiency of other cations in the ecosystem. Also, high sodium concentrations could result to degraded soil composition and impede water permeation in soils. Exposure to high concentration of heavy metals in sediments caused gills, kidney, and neuro-system damaged, and reduced rates of cell division in marine life [31]. Chronic exposure to heavy metals at low concentrations reduces plant photosynthesis and growth and alters the richness and taxonomical configuration of wildlife [32].

PW also impacts on oil and gas production equipment, process, and economics. Production solids can block flow of fluids in the well or the PW treatment facility which could led to shut down. PW bearing finely textured solid diminishes removal efficacy of oil-water separation equipment, thus resulting in high oil and grease concentration in effluent [33]. Certain production solids and scales could also form oily slurry in the equipment used for production, thereby necessitating frequent maintenance. The activities of bacteria domiciled in PW causes corrosion of equipment, precipitation of iron sulphide, contamination of natural gas and formation of stubborn emulsions [34]. Scales can be formed during production due to ionic reactions in a highly saturated PW to form precipitates at lowered pressure and temperature. The heavy metals in PW and scales which are mostly carbonates and sulfates of calcium, barium, and iron, cause blockage of well screen and pipes, thereby restricting hydrocarbon flow that results in drop in oil production and shutdown of oil well [35].

In recent times, PW disposal into the environment is regulated to include not only non-polar components in the PW, but also dissolved hydrocarbons. The maximum discharge limit for oil content in PW has been agreed by the Oslo Paris Convention (OSPAR) to be 30 mg/l and the Nigerian regulatory body, like other innovative countries (Australia, Denmark, Norway, and the United Kingdom), has conformed to this agreement and stipulated PW disposal specifications [36] as shown in Table 1.

Table 1. *Produced Water Discharge Limits in Nigeria [36].*

Effluent Characteristics	Unit	Compliance Limits: Maximum for any consecutive 30 days Period	
		Inland	Nearshore
pH	-	6.5 – 8.5	6.5 – 8.5
Temperature	^{o}C	Ambient ±2	Ambient ±2
Total Hydrocarbon Content	mg/l	10.0	30.0
Salinity as Cl	mg/l	600.0	2,000.0
Turbidity	NTU	>10	>15
Total Dissolved Solids (TDS)	mg/l	2,000.0	5,000.0
Total Suspended Solids (TSS)	mg/l	>30.0	>50.0
Chemical Oxygen Demand (COD)	mg/l	40.0	125.0
Biological Oxygen Demand (BOD_5)	mg/l	10.0	125.0
Lead (Pb)	mg/l	0.05	No limit
Total Iron (Fe)	mg/l	1.0	No limit
Copper (Cu)	mg/l	1.5	No limit
Total Chromium	mg/l	0.05	0.5
Zinc (Zn)	mg/l	1.0	5.0
Nickel (Ni)	mg/l	0.07	No limit

PW need to be managed appropriately because of its hazardous contents which pose risks to health and safety of the ecosystem. PW management is challenging and incurs additional costs to oil and gas production. PW management approach for a given oil and gas field depends on the physicochemical properties of the PW, locality, and available resources [18]. The strategies and technologies for managing PW could be organized into three-layer pollution prevention pyramid [19]. The first tier is source minimization of water, which is achieved through processes modification, technologies adaptation, or products substitution so that less water is produced. Minimization of water is challenging, however restricting water from permeating the well bore can be achieved using mechanical blocking devices or chemicals that shut up water producing channels or cracks inside the formation. Source minimization of PW, where practicable, can save cost and reduce the negative impact of untreated PW.

The second tier, which is the recycle/reuse, is considered when the water cannot be handled through minimization. The PW is reinjected into an underground formation for improved or enhanced oil recovery. In onshore fields, while larger percentage of water produced is reinjected to sustain formation pressure and to push oil out from the reservoir, some percentage of it is injected merely for disposal. PW can also be reused for agriculture and recreational purposes if it meets the required quality. In such cases, produced water is re-classified as a valuable commodity. However, in most cases, PW does not meet such requirements for recycle/reuse or disposal. It must be treated adequately to fit the physicochemical requirement for business and environmental sustainability.

As an emphatic third tier PW management option, treatment methods for oil and gas fields PW are categorized into physical, chemical, and biological methods [3, 5, 11, 18, 19, 37, 38]. Physical method of PW treatment commonly used in the Niger Delta oilfields includes, gravitational separation and skimming, flotation, hydrocyclones, filtration, evaporation [39-41]. Chemical treatment method used in PW includes chemical precipitation, oxidation, electrochemical process, photocatalytic treatment, ozonisation, room temperature ionic liquids and demulsification [42, 43]. Biological treatment is a secondary treatment method in which microbial consortium either in suspended or attached configuration degrades contaminants in wastewater under aerobic or anaerobic environment. Microbial degradation of petroleum hydrocarbon employs the catalytic prowess of microorganisms to eliminate organo-pollutants [44-46].

Though several works have been carried out to characterize PW and investigate PW treatment in the Niger Delta oilfields, but the inherent challenges and innovative options for actualizing fit-for-purpose PW quality are very scanty. Therefore, the aim of this work is to characterize PW from three different oilfield facilities, review their PW treatment methods, their challenges and proffer innovations that could resolve their challenges.

2. Materials and Methods

2.1. PW Sampling and Characterization

PW samples as shown in Figure 1 were collected from an oilfield Flow Station, crude oil processing and natural gas processing facilities and preserved according to standards [47-49]. The samplings were carried out three times daily for one week to ascertain the PW composition and quality, and the averaged concentrations were reported. Temperature and pH were measured in-situ. The samples were taken in an iced box to the laboratory for analysis. Standard methods, as shown in Table 2, were used to analyze the samples. Analytical grade chemicals were used for the analyses.

Figure 1. *Oilfield Produced Water Sample.*

Table 2. *Analytical Methods used for PW Characterization.*

PW Characteristics	Method
Temperature, ℃	In situ Thermometric
pH@ 25 ℃	APHA 4500-H+B
Conductivity@ 25 ℃, ms/cm	APHA 2510
Total Alkalinity, mgCaCO$_3$/l	APHA 2320B
Total Hardness, mgCaCO$_3$/l	APHA 2340C
Total Dissolved Solids, TDS, mg/l	APHA 2540C
Total Suspended Solids, TSS, mg/l	APHA 2540D
Bicarbonate	APHA 2320B
Salinity, (Cl^{-1}, mg/l)	APHA 4500-Cl-B
Chemical Oxygen Demand, COD, mg/l	APHA 5220D
Total Oil Content, TOC, mg/l	ASTM D7066
n-Alkanes	GC-MS
Mono-Aromatics	GC-MS
PAHs	GC-MS
Sulphate	HACH 8051
Barium, Ba, mg/l	APHA 3111B
Calcium, Ca, mg/l	APHA 3500-Ca-B
Chromium, Cr, mg/l	HACH 8023
Copper, Cu, mg/l	HACH 8056
Iron, Fe	ASTM D4691-17
Lead Pb+	APHA 3111B
Magnesium, Mg, mg/l	APHA 3500-Mg-B
Manganese, Mn, mg/l	APHA 3111B
Nickel, Ni, mg/l	APHA 3111B
Sodium, Na, mg/l	APHA 3111B
Zinc, Zn, mg/l	HACH 8009

2.2. Description of the PW Treatment Units

2.2.1. PW Treatment Method at the Flow Station

Gravitational separation is used as the first step of PW treatment in most oil and gas Flow Stations in the Niger Delta, to reduce the volume of PW transported to oil and gas processing terminals. The two-phase and three phase separators are used depending on the reservoir fluid. The concerted influence of gravity, buoyancy, intermolecular forces, and fluid resistivity facilitates the dispersed oil phase to float. Finely distributed gas bubbles are introduced into the system to enhance the flotation of oil, after which, the aggregation of oil sheet is skimmed from the water. Figure 2 Shows the schema of the PW treatment.

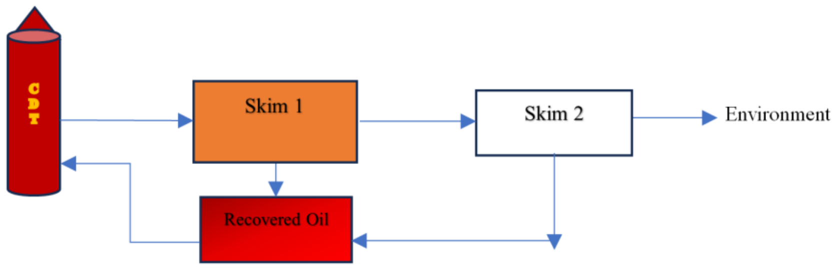

Figure 2. *Schema of PW Treatment at the Flow Station.*

2.2.2. PW Treatment Method at the Crude Oil Processing Terminal

Induced Gas flotation (IGF) combined with corrugated plate interceptors (CPI) and skimmers, as shown in Figure 3 are used in the crude oil processing facility in Niger Delta oilfields to treats PW.

PW from the crude oil dehydration processes flow into the CPI units which are designed to reduce, at a certain flow rate, the inlet total suspended solids (TSS) and oil/grease concentrations to <40 mg/l and 30 parts per million (ppm), respectively. The PW exits the CPI units to the IGF units, where flocculating chemical is injected both upfront of and in the IGF units to aid flotation and coalescence of residual oil. The IGF units aided by flocculating agent further reduces the oil and grease concentration <10 mg/l. The PW exits the IGF units by gravity to the skimming basin/water disposal pit (WDP), where an oil skimmer pipe, which extends horizontally along the WDP, removes any remaining oil that CPI and IGF units could not remove, and the treated PW exits the WDP through a trash screen and piped into sea.

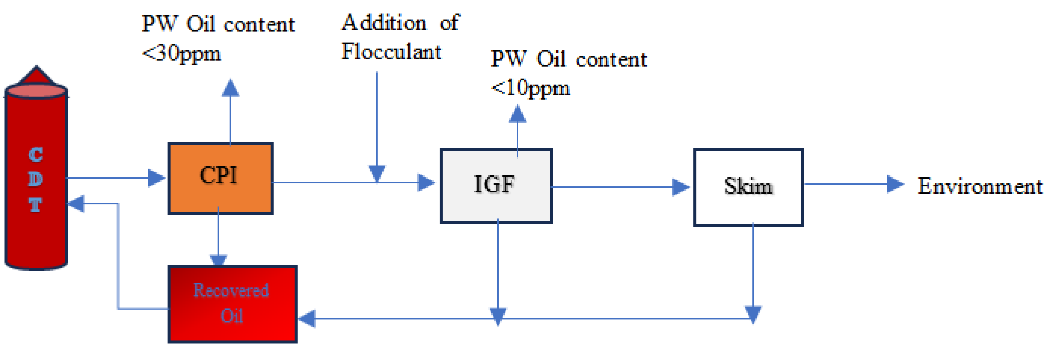

Figure 3. *Schema of PW Treatment at the Crude oil Processing Facility.*

2.2.3. PW Treatment Method at the LNG Processing Terminal

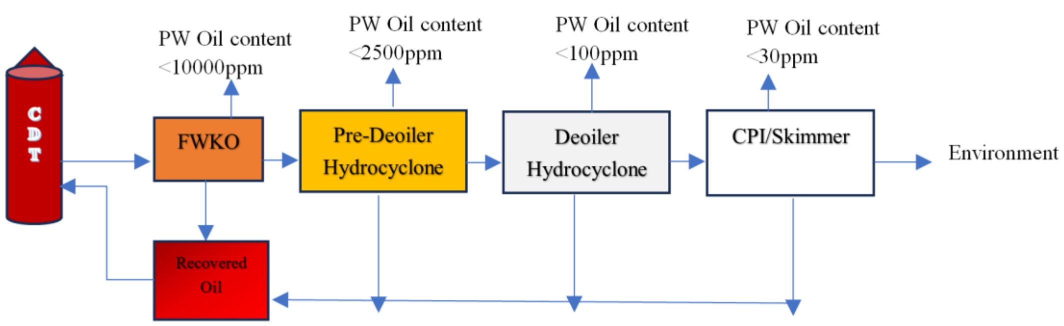

Figure 4. *Schema of PW Treatment at the LNG/Condensate Processing Facility.*

The liquified natural gas (LNG) processing facility uses deoiler hydrocyclone combined with CPI and Skimmers, as shown in Figure 4, to treat its PW. The deoiler hydrocyclone was designed to reduce oil-in-water to <100 ppm, total suspended solids (TSS) to <53.0 ppm, chlorides to 12000 mg/l, and sand to <23 mg/l, required for injection to disposal wells. CPI and skimmers are adjoined to further reduce the PW for disposal into the estuary. PW from the gas and condensate dehydration processes flow into the deoiler free water knock out (FWKO) to reduce oil content to |<10000 ppm. The PW exits the deoiler FWKO to pre-deoiler unit for further reduction of oil and grease concentration to <2000 mg/l. The PW exits the pre-deoiler unit to the deoiler hydrocyclone to reduce oil-n-water content to <100 ppm. The PW exit the deoiler hydrocyclone to a disposal well or to CPI unit and a skim basin for further reduction, after which the treated PW exits through a trash screen and piped into the estuary.

2.2.4. PW Treatment Using Innovative Solutions

The innovative technology to solving the challenge of PW quality incorporates gravity separation, biological and membrane technologies, as shown in Figure 5. The extant physicochemical treatment techniques used in the oilfield facilities are complemented with modular biological treatment units and a membrane system, as shown in Figure 6. Mechanical techniques (gravity separation) are used to pre-treat the PW, followed by bio-oxidation using a modular bio-oxidation unit (Bio-Unit) and polishing using ultra/nanofiltration (UF/NF). The Bio-Unit + UF/NF is selected because it requires minimal space, energy consumption, and non-usage of chemicals.

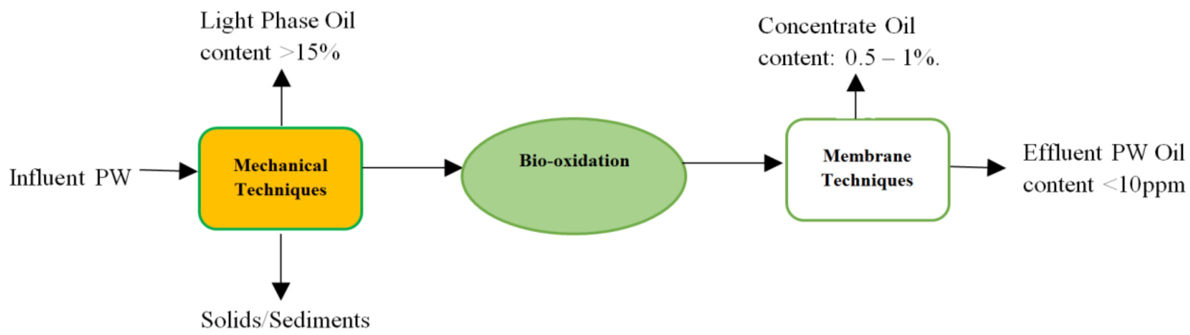

Figure 5. PW Treatment via Gravity Separation-Biooxidation-Membrane Systems.

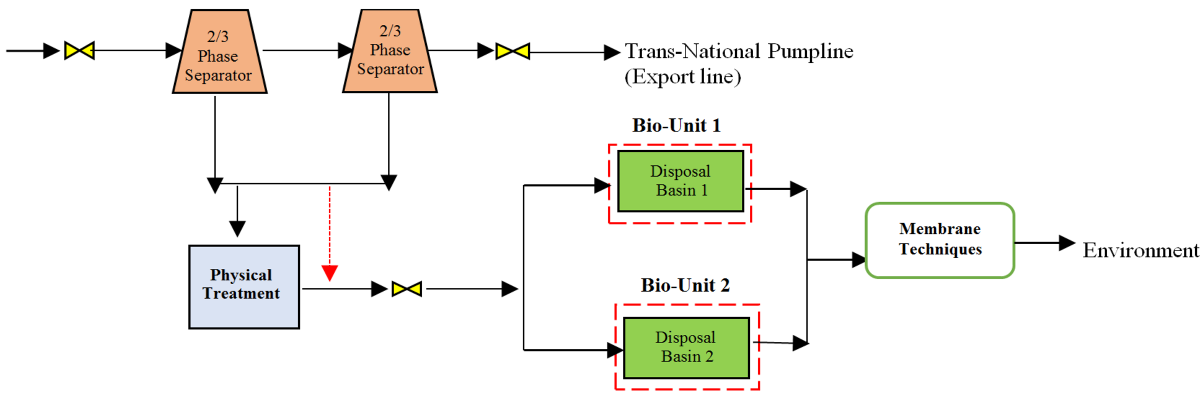

Figure 6. Extant PW Treatment Retrofitted with Modular Bio-Units and Ultra/Nanofiltration.

3. Results and Discussion

The result of the analyses to characterize the PW is shown in Table 3. The result highlights the biogeochemical homogeneity of PW from the Niger Delta oil and gas fields. The result shows that the PW contains high total dissolved solids (TDS), bicarbonates, salinity, chemical oxygen demand (COD), sulphates, and organic constituents. Also, while the PW from these fields were laden with calcium, sodium and magnesium, other metals were in minute concentrations. The PW temperatures were ≥36 ℃, which indicates that the PW could precipitates metallic carbonates and sulphates. Injecting this PW into well cuttings or reservoir could cause plugging of the wells, pipelines, and equipment due to scale formation. Also, the sodium chloride in the PW reacting with oxygen could cause corrosion of equipment and pipeline. The result also shows that the concentrations of organic constituent in PW from gas fields were higher than that from the oil fields. The result indicates that the concentrations of the various constituents in the PW from the Flow Station, Crude oil processing and LNG processing facilities are higher than required for injection into well cuttings or disposal to environment. Thus, there is need for treatment of the PW.

Table 3. Niger Delta Oil and Gas Fields PW Characteristics.

Parameter	Flow Station	Crude Oil Processing Facility	LNG Processing Facility
Physicochemical Characteristics			
Temperature, ℃	36.0	38.5	39.8
Density (kg/m^3)	1007.0	1007.0	1006.0
pH@ 25 ℃	7.89	7.91	7.87
Conductivity@ 25 ℃, ms/cm	24.63	19.52	14.66
Total Alkalinity, mg$CaCO_3$/l	957.3	1282.0	871.14
Total Hardness, mg$CaCO_3$/l	224.7	361.25	120.51
Total Dissolved Solids, TDS, mg/l	14584.0	11875.0	9392.43
Total Suspended Solids, TSS, mg/l	289.0	300.0	210.0
Bicarbonate	1055.0	1340.0	1049.75
Salinity, (Cl^{-1}, mg/l)	5491.80	6403.21	4589.15
Chemical Oxygen Demand, mg/l	588.1	618.0	605.2
Organic Constituents			
Oil and Grease, O&G, mg/l	476.9	485.2	594.3
n-Alkanes, mg/l	458.1	433.0	527.5
Mono-Aromatics, mg/l	18.50	17.8	49.2
PAHs, mg/l	6.20	5.96	11.7
Inorganic Constituents			
Sulphate, mg/l	63.1	56.8	60.75
Barium, Ba, mg/l	6.00	8.23	7.41
Calcium, Ca, mg/l	167.3	159.27	132.89
Chromium, Cr, mg/l	0.04	0.05	0.02
Copper, Cu, mg/l	0.36	0.32	0.40
Iron, Fe	0.15	0.56	4.80
Lead Pb+	0.87	0.65	0.73
Magnesium, Mg, mg/l	45.5	75.4	39.39
Manganese, Mn, mg/l	1.36	1.13	1.05
Nickel, Ni, mg/l	0.5	0.38	0.42
Sodium, Na, mg/l	92.0	98.6	85.7
Zinc, Zn, mg/l	0.32	0.21	0.30

The results of the treated PW from the three produced water treatment (PWT) configurations and the PWT retrofitted with modular Bio-Unit + Ultra/Nanofiltration are shown in Table 4. The results show that some parameters did not meet the requirement for injection or disposal into the environment. The TDS concentrations in the treated PW from the three PWT configurations were 6105.9 mg/l, 4485.0 mg/l, and 4316.42 mg/l, indicating 58.1%, 62.2% and 58.3% reduction, respectively. However, the TDS concentration in the treated PW from the Flow Station PW treatment configuration did not meet the specification (5000.0 mg/l) by Nigerian Upstream Petroleum Regulatory Commission (NUPRC) for nearshore disposal.

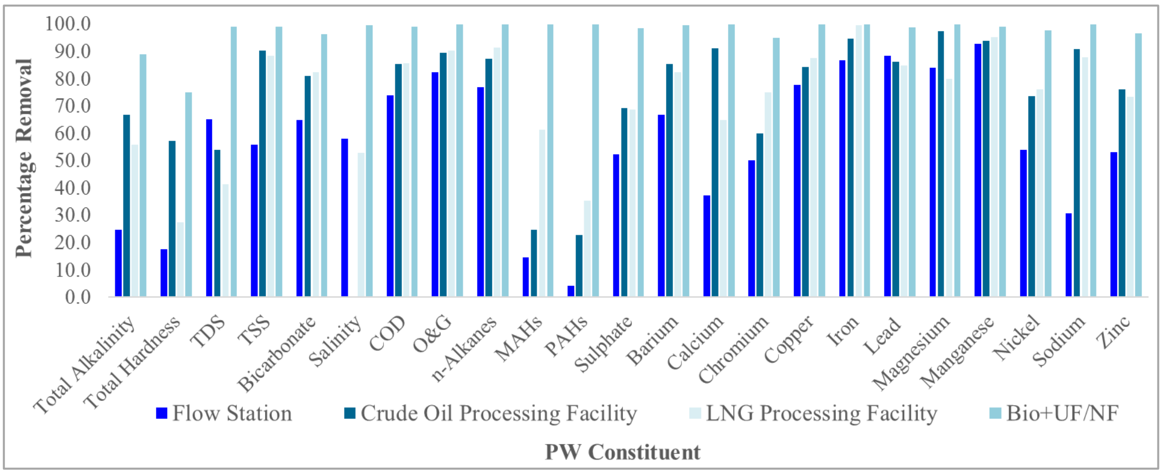

Figure 7. *Percentage Removal of PW Constituents by the Different PW Treatment Configurations.*

Table 4. *Quality of Treated PW from the three PWT Configurations and the PWT retrofitted with modular Bio-Unit + Ultra/Nanofiltration.*

Parameter	Flow Station	Crude Oil Processing Facility	LNG Processing Facility	Bio-Unit + UF/NF
Physicochemical Characteristics				
Temperature, ℃	27.0	28.2	29.0	26.1
Density (kg/m^3)	1006.0	1004.5	1004.5	1.002.3
pH@ 25 ℃	7.80	7.78	7.79	7.46
Conductivity@ 25 ℃, ms/cm	13.87	11.55	6.9	3.13
Total Alkalinity, mgCaCO$_3$/l	722.1	427.3	384.0	97.7
Total Hardness, mgCaCO$_3$/l	185.3	154.6	87.4	30.0
Total Dissolved Solids, TDS, mg/l	6105.9	4485.0	4316.42	84.1
Total Suspended Solids, TSS, mg/l	121.8	28.9	18.2	2.05
Bicarbonate	369.5	256.4	185.6	39.1
Salinity, (Cl^{-1}, mg/l)	2411.0	2218.6	2165.4	23.2
Chemical Oxygen Demand, mg/l	153.0	148.1	141.2	5.60
Organic Constituents				
Oil and Grease, O&G, mg/l	84.7	51.5	58.0	1.5
n-Alkanes	106.1	55.2	46.0	1.2
Mono-Aromatics	15.80	13.4	15.2	0.07
PAHs	5.95	4.60	7.56	0.03
Inorganic Constituents				
Sulphate, mg/l	30.1	17.5	19.1	1.00
Barium, Ba, mg/l	2.00	1.21	1.30	0.01
Calcium, Ca, mg/l	23.4	14.3	11.6	0.05

Parameter	Flow Station	Crude Oil Processing Facility	LNG Processing Facility	Bio-Unit + UF/NF
Chromium, Cr, mg/l	0.02	0.02	0.02	0.001
Copper, Cu, mg/l	0.08	0.05	0.05	0.001
Iron, Fe	0.02	0.03	0.02	0.01
Lead Pb+	0.10	0.09	0.11	0.01
Magnesium, Mg, mg/l	7.30	2.06	1.88	0.01
Manganese, Mn, mg/l	0.10	0.07	0.05	0.01
Nickel, Ni, mg/l	0.23	0.10	0.10	0.01
Sodium, Na, mg/l	21.0	8.50	7.2	0.025
Zinc, Zn, mg/l	0.15	0.05	0.08	0.01

The salinity contents in the treated PW from the three PWT configurations were 2411.0 mg/l, 2218.6 mg/l, and 2165.4 mg/l, respectively. It shows that the treated PW salinity content was slightly above NUPRC specification (2000.0 mg/l) for nearshore disposal. The COD concentrations in the treated PW from the three PWT configurations were 153.0 mg/l, 148.1 mg/l, and 141.2 mg/l, respectively, which were above the NUPRC standard (125.0 mg/l). The O&G concentration in the treated PW were 84.7 mg/l, 51.5 mg/l, and 58.0 mg/l, respectively, which also were above regulatory stipulation (30.0 mg/l) for nearshore disposal.

The result also indicates that the concentrations of the inorganic constituents was reduced, considerably. Sulphate concentrations (63.0 mg/l, 56.8 mg/l, and 60.75 mg/l) were reduced to 30.1 mg/l, 17.5 mg/l, and 19.1 mg/l for the three PWT configurations, respectively. Calcium concentrations (167.3 mg/l, 159.27 mg/l, and 132.89 mg/l) were reduced to 23.4 mg/l, 14.3 mg/l, and 11.6 mg/l, by the three PWT configurations, respectively. Sodium concentrations (92.0 mg/l, 98.6 mg/l and 85.7 mg/l) were reduced to 21.0 mg/l, 8.5 mg/l, and 7.2 mg/l, respectively, by the three PWT configurations. The high removal of inorganic constituents could be attributed to scales and corrosion inhibitors, and flocculants that are injected upstream and downstream the CPI/IGF units. The quality of treated PW from the PWT configurations of the crude oil processing and the LNG processing facilities were better than that of the Flow Station. This is because at PW treatment at the Flow Station is skeletal, as its main purpose is to drastically reduce the volume of water content in the crude oil or natural gas before transportation to the processing facility. While at the processing terminals, more PW treatment equipment is installed to handle PW to forestall corrosion and plugging of production equipment.

The overall results indicates that the extant PWT configurations cannot adequately remove petroleum hydrocarbon constituents to environmentally admissible standards. Nwokoma and Dagde (2012; 2023) investigated the efficiency of this PW treatment unit and reported that the technique could not adequately remove soluble aromatics from the PW, though other parameters met the environmental discharge requirement. It may also suggest that the major objective of PW treatment by the oil and production operators is to protect production equipment than the environment. Figure 7 depicts that the PW quality resulting from the innovative modular Bio-Unit + Ultra/Nanofiltration had superior performance when compared to the PW quality from the extant PW treatment configurations. The innovative modular Bio-Unit + Ultra/Nanofiltration achieved 99.1%, 99.7%, 99.8%, 99.8%, 99.7% removal of COD, O&G, n-alkanes, MAHs and PAHs from the PW. Also, the modular Bio-Unit + Ultra/Nanofiltration achieved more than 95% removal of the inorganic constituents in the PW.

4. Conclusion

The increasing PW volume, which has overwhelmed the conventional PW treatment plants in the Niger Delta oilfields, calls for innovative fit-for-purpose and fit-for-future PW treatment technologies, that will withstand rising water-in-oil content from matured oil/gas reservoirs, meet specifications for reinjection, recreation and/or compliance with stricter environmental regulations. It is also pertinent to note that, due to biogeochemical intricacies of PW, there is no standalone method that can guarantee PW quality specifications, rather a combination of more treatment techniques. Therefore, based on the Niger Delta PW characteristics, the appropriate techniques for handling and treatment of the PW should be a robust onsite end of pipe PW treatment, especially at the Flow Stations, where PW is commonly disposed into the estuaries. The configuration for the PW treatment should include a combination of gravity separation, biological and membrane technologies, as shown in Figures 5 and 6. The upfront gravity separation serves as the PW pre-treatment, while the modular bio-oxidation unit (Bio-Unit) and ultrafiltration membrane separation serve as secondary and polishes stages, respectively.

The findings from this research indicates that this innovative configuration will not only resolve the challenges of PW handling and treatment, but it could turn PW from disposable to reusable commodity.

Abbreviations

BTEX	Benzene, Toluene, Ethylbenzene, Xylene
CDT	Crude Dehydration Tank
COD	Chemical Oxygen Demand
CPI	Corrugated Plate Interceptor
FWKO	Free Water Knock Out
IGF	Induced Gas Flotation
LNG	Liquified Natural Gas
MAH	Monocyclic Aromatic Hydrocarbons
NUPRC	Nigerian Upstream Petroleum Regulatory Commission
O&G	Oil and Grease
PAH	Polycyclic Aromatic Hydrocarbons
PW	Produced Water
PWT	Produced Water Treatment
TDS	Total Dissolved Solids
WDP	Water Disposal Pit

Author Contributions

Kenneth Kekpugile Dagde: Conceptualization, Formal analysis, Validation, Writing - review and editing, Supervision, Resources

Darlington Bon Nwokoma: Conceptualization, Methodology, Writing – original draft, Visualization, Investigation, Formal analysis, Resources

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Conflicts of Interest

The authors declare no conflicts of interest.

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