Petroleum Research 11 (2026) 633–640

Contents lists available at ScienceDirect

Petroleum Research

journal homepage: http://www.keaipublishing.com/en/journals/petroleum-research/

Full Length Article

Physicochemical characterization of oilfield produced water and its treatment constraints

Sandro Duarte César [a,*], Debbie De Jager [a,b], Mahomet Njoya [b]

[a] Department of Chemical Engineering, Faculty of Engineering & the Built Environment, Cape Peninsula University of Technology, P.O. Box 1906, Bellville, 7535, South Africa

[b] Bioresource Engineering Research Group (BioERG), Department of Biotechnology, Cape Peninsula University of Technology, P.O. Box 652, Cape Town, 8000, South Africa

A R T I C L E I N F O

Article history:
Received 17 March 2025
Received in revised form
27 October 2025
Accepted 28 October 2025
Available online 1 November 2025

Keywords:
Oilfield produced water
Water characterization
Physicochemical analyses
Biodegradability index
Water remediation
Angolan offshore

A B S T R A C T

Produced water is the largest waste stream generated during oil and gas production, presenting significant environmental risks due to its complex chemical composition. Characterizing the contaminant profile of produced water is crucial for assessing its environmental impact, ensuring compliance with discharge standards, and developing effective pollution mitigation strategies. This study characterizes untreated produced water from Angolan offshore Block 15 over a 50-day sampling period, analyzing over 30 target constituents. Results reveal substantial variability in key parameters, including chemical oxygen demand (394.02–526.00 mg/L), biochemical oxygen demand (9.80–20.40 mg/L), phenol (2.70–4.12 mg/L), benzene, toluene, ethylbenzene and xylene (BTEX, 2.77–7.00 mg/L), polyaromatic hydrocarbons (0.20–1.20 mg/L), total organic compounds (248–918.45 mg/L), total oil and grease (19–206 mg/L), and total petroleum hydrocarbons (12–105.02 mg/L). Metals and anions exhibited significant fluctuations, with sodium ranging from 1167.77 to 2100.00 mg/L and chloride from 400 to 2146.84 mg/L. The biodegradability index (0.028) indicates limited potential for biological treatment due to toxic and refractory organics. The results emphasize the necessity for advanced treatment technologies and stricter environmental regulations to reduce contaminant discharge and minimize the ecological footprint of offshore oil production.

1. Introduction

Produced water is the largest waste stream associated with oil and gas production, consisting of both formation water (naturally occurring water in the reservoir) and injection water (used for enhanced recovery and well stimulation) (Olajire, 2020; Nasiri et al., 2017; Zheng et al., 2016). The composition of produced water varies significantly depending on geological formations, extraction techniques, and operational conditions, posing challenges for treatment and disposal. Contaminants commonly found in produced water include hydrocarbons (aliphatic, aromatic, and polar fractions), heavy metals, salts, and naturally occurring radioactive materials (NORMs), many of which have ecotoxicological and regulatory implications (Jimenez et al., 2018).

Over the last decade, the volume of produced water generated globally has increased due to intensified oil and gas activities and aging reservoirs. From 2017 to 2022, global produced water generation rose from approximately 139 billion barrels (bbl.) to 170 billion bbl. (Energy Institute, 2023). North America remains the largest contributor, with an increase of 11.7 billion bbl. over this period, reflecting the high activity in shale oil and gas production. In contrast, Europe and Central Asia experienced moderate growth despite fewer new developments, while Southern Asia produced comparatively lower volumes, consistent with its smaller hydrocarbon industry (Energy Institute, 2023; OPEC, 2023; Amakiri et al., 2022).

While extensive research has been conducted on the chemical composition of produced water from major oil-producing regions such as Nigeria, Malaysia, India, China, Brazil, the Gulf of Mexico, Qatar, and Iraq (Amakiri et al., 2023; Akinade, 2013; AlAnezi et al., 2018; Chikwe and Okwa, 2016; Dórea et al., 2007; Eldos et al.,

* Corresponding author.
E-mail address: sandro.cesar01@gmail.com (S.D. César).
Peer review under the responsibility of Editorial Office of Petroleum Research.

https://doi.org/10.1016/j.ptlrs.2025.10.003
2096-2495/

2022; Jiang et al., 2022; Kumar et al., 2022; Lahlou et al., 2020; Lu et al., 2006; Ma et al., 2009; Obunwo and Chukwudi, 2015; Razak et al., 2022), there is a notable lack of publicly available studies on the physicochemical and organic composition of produced water from Angolan offshore oilfields. Most existing data on produced water discharge and treatment regulations in Angola comes from industry reports and unpublished operator assessments, which are not readily accessible for comparative analysis. This knowledge gap is particularly significant considering that Angola, with an estimated 9 billion bbl of crude oil reserves and 11 trillion cubic feet of natural gas, is one of Africa's top oil producers (César, 2022; Energy Institute, 2023). Offshore oilfields in the Lower Congo Basin and Cabinda region contribute substantially to production, which reached 1.4 million bbl/day in 2022, generating an estimated 5 billion bbl. of produced water.

Given the lack of published studies detailing the chemical composition and pollutant load of Angola's produced water, this study provides an initial characterization of the physicochemical and organic properties of untreated produced water from Angola's offshore Block 15. Additionally, it assesses the biodegradability of organic contaminants using the biodegradability index (BOD_5/COD ratio) to evaluate the feasibility of biological treatment strategies. The findings will help inform treatment strategies, optimize produced water management, and support environmental protection efforts in Angola's oil and gas sector.

2. Materials and methods

2.1. Site description

The study was conducted at an undisclosed FPSO operating in the Angolan offshore Block 15 region that has been in operation for a decade (Fig. 1). After extraction from the offshore wells, the hydrocarbon mixture is dosed with an emulsion-breaking chemical and routed to a three-phase separator. The separated oil is washed and dehydrated, the gas is compressed for use as fuel gas or gas injection and the water is duly treated for overboard discharge into the marine environment.

2.2. Produced water sampling

Untreated produced water samples were collected from the high-pressure three-phase separator's water outlet at 6:00 a.m., 12:00 p.m., and 6:00 p.m. over a 50-day period. This timeframe was selected to capture diurnal variations in production operations, separator performance and chemical dosing cycles. Sampling times were chosen to ensure that both peak and off-peak operational conditions were represented, providing a comprehensive dataset for produced water characterization. The 50-day duration aligns with similar studies in offshore environments, allowing for a robust assessment of variability in produced water composition. Samples were collected in chemically clean glass and polyethylene bottles, which were rinsed with produced water before filling and sealed with Teflon-lined lids to prevent contamination.

The specific bottles were chosen based on the type of analysis as follows:

- 1 L glass bottles: Used for Benzene, Toluene, Ethylbenzene and Xylene (to prevent the loss of volatile organic compounds), Polycyclic Aromatic Hydrocarbons, Total Organic Carbon, Dissolved Organic Carbon (to avoid contamination and adsorption of organic compounds), Total Oil and Grease, Total Petroleum Hydrocarbons (for chemical inertness and resistance to solvents), and Biochemical Oxygen Demand over five days (for 5-day storage).
- 500 mL polyethylene bottles: Used for pH, Conductivity, Dissolved Oxygen (measured immediately without long-term storage), turbidity (unaffected by container material), alkalinity (for titration-based methods), Total Dissolved Solids, Total Suspended Solids, Chemical Oxygen Demand, phenol, anions, and metal concentrations (for acidified samples to prevent metal contamination).

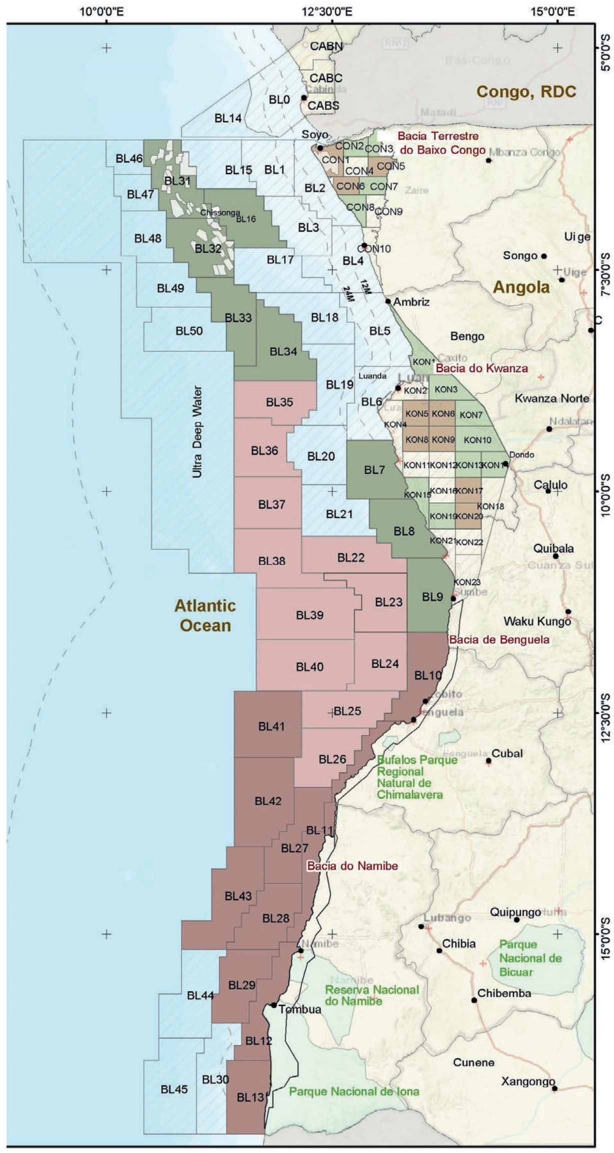

Fig. 1. Angolan offshore oilfield blocks (adapted from ANPG, 2019).

For in-house laboratory analysis, samples were immediately analysed upon arrival. For external laboratory analysis, samples were transported under refrigerated conditions (4 °C) every Mondays, Wednesdays and Fridays.

2.3. Produced water analyses

Produced water analyses were conducted using standardized analytical techniques, ensuring compliance with regulatory and scientific standards. pH, conductivity, and dissolved oxygen (DO) were measured using a Hach® HQ4300 portable multi-meter with PHC20101, CDC40101, and LDO10105 probes, following EPA methods 9040C, 2510B, and 360.2, respectively. Turbidity was determined using a Hach® 2100Q turbidimeter (EPA 180.1), while alkalinity was quantified through titration (EPA 2320B).

Gravimetric analysis was employed for Total Dissolved Solids (TDS) and Total Suspended Solids (TSS) using 0.15 μm filters (EPA 2540C and 2540D). Chemical Oxygen Demand (COD) and phenol concentrations were determined using a Hach® DR3900 spectrophotometer with EPA 410.4 (COD) and EPA 420.1 (phenols). Biochemical Oxygen Demand (BOD_5) was measured with a Hach® HQ4300 m using probe LBOD101 (EPA 5210B), ensuring accurate quantification of biodegradable organic matter.

Total Organic Carbon (TOC) and Dissolved Organic Carbon (DOC) were analysed using a Shimadzu® TOC-V CSH analyzer (EPA 415.3, 5301). Total Oil and Grease (TOG) and Total Petroleum Hydrocarbons (TPH) were measured via n-hexane liquid-liquid extraction followed by infrared spectroscopy (EPA 1664B), with silica gel treatment to separate non-polar fractions.

Benzene, Toluene, Ethylbenzene and Xylene (BTEX) analysis was conducted using a Tekmar–Dohrmann® Velocity XPT purge-and-trap system coupled with an Agilent® 7890 gas chromatograph (GC) and an Agilent® 5977A mass spectrometer (MS) (EPA 8260C). Total Polycyclic Aromatic Hydrocarbons (PAHs) were quantified by liquid-liquid extraction followed by GC-MS analysis (EPA 3510C and 8270C). TOC and DOC (the latter using a 0.45 μm filter) were analysed using a Shimadzu® TOC-V CSH analyser in line with EPA 415.3 and 5301. Metal concentrations were measured in acidified samples by means of inductively coupled plasma (ICP) - optical emission spectrometry (OES) using an Agilent® 5800 ICP-OES, based on EPA 200.7. Anions such as bromide, chloride and sulfate were determined with a Thermo Scientific® Dionex ICS 3000 SP ion chromatography system, following EPA 300.1.

3. Results

3.1. Produced water inorganic profile

Table 1 represents the concentrations of metals and anions in 150 produced water samples, averaged across three daily measurements over a 50-day period. The concentration of aluminum (Al) in the produced water averaged 3.07 mg/L, ranging from a minimum of 2.00 mg/L to a maximum of 4.74 mg/L. Calcium (Ca) concentration, averaging 13.24 mg/L, were relatively stable with a standard deviation of 2.86 mg/L and a range of 10.40 mg/L to 18.97 mg/L. Iron (Fe) concentration averaged 4.10 mg/L and ranged from 1.20 mg/L to 6.59 mg/L and the nickel (Ni) concentration exhibited a wide range (28.00 mg/L to 621.24 mg/L), with high variability reflected in the 25th and 75th percentiles of 141.93 mg/L and 456.15 mg/L, respectively. Elevated concentrations of nickel suggest contamination from corrosion of nickel-based alloys used in production equipment (Neff et al., 2011). The sodium (Na) concentration was exceptionally high, averaging 1729.09 mg/L with a range of 1167.77 mg/L to 2100.00 mg/L. The high standard deviation of 325.14 mg/L and median concentration of 1796.11 mg/L suggest either seawater intrusion or the inherent high salinity of the reservoir formation (Jiang et al., 2022).

Table 1
Results of comprehensive elements analyses on the produced water from Angola block 15.

	Unit	Average	Range
Aluminum	mg/L	3.07 ± 1.03	2.00–4.74
Barium	mg/L	2.63 ± 0.8	1.42–3.82
Calcium	mg/L	13.24 ± 2.86	10.40–18.97
Chromium	mg/L	1.80 ± 0.72	0.80–3.00
Copper	mg/L	1.37 ± 0.68	0.60–2.58
Iron	mg/L	4.10 ± 1.67	1.20–6.59
Potassium	mg/L	214.12 ± 121.53	45.00–415.22
Magnesium	mg/L	44.99 ± 8.5	30.66–61.00
Sodium	mg/L	1729.09 ± 325.14	1167.77–2100.00
Nickel	mg/L	314.07 ± 179.33	28.00–621.24
Lead	mg/L	0.66 ± 0.54	0.00–1.88
Silicon	mg/L	67.06 ± 17.08	39.00–101.31
Strontium	mg/L	35.63 ± 23.22	14.00–83.08
Zinc	mg/L	0.67 ± 0.31	0.14–1.22
Bromide	mg/L	101.46 ± 20.91	71–137.91
Chloride	mg/L	1206.72 ± 538.33	400–2146.84
Sulfate	mg/L	151.49 ± 66.87	64–271.91

Bromide ranged from 71 to 137.91 mg/L, showing moderate variability. Chloride, with concentrations between 400 and 2146.84 mg/L, exhibits the highest variability, indicating significant fluctuations. Sulfate levels ranged from 64 to 271.91 mg/L, displaying moderate variability with occasional peaks.

3.2. Produced water psychochemical profile

The statistical results of the physicochemical and organic characteristics of the analysed oilfield produced water are presented in Table 2 and the graphical representation of the results are illustrated in Figs. 2 and 3. The pH measurements ranged from 4.81 to 8.17 with an average of 6.36, indicating a slightly acidic to neutral environment overall. The conductivity ranged from 24.8 mS/cm to 32.67 mS/cm, with a mean of 28.34 mg/L and the dissolved oxygen (DO) values ranged from 3.09 mg/L to 5.52 mg/L, with a mean of 4.3 mg/L. Turbidity and alkalinity ranged from 29 NTU to 276.47 NTU and 81 mg/L $_{CaCO3}$ to 577.04 mg/L $_{CaCO3}$, with an average of 139.93 NTU and 324.7 mg/L $_{CaCO3}$, respectively.

Total dissolved solids (TDS) exhibited an average concentration of 14 256 mg/L and a median of 14 117.07 mg/L. The values ranged from a minimum of 11 948.38 mg/L to a maximum of 16 582.19 mg/L, with a spread of 4633.81 mg/L. Total suspended solids (TSS), which may include drifting particles such as sand, silt, algae, plankton, and sediments, ranged from 314.00 mg/L to 502.81 mg/L, with an average of 345.89 mg/L. The distribution was slightly right-skewed and exhibited heavier tails than a normal distribution, suggesting occasional high-concentration outliers.

Chemical oxygen demand (COD) ranged from 394.02 to 526.00 mg/L (mean: 470.82 mg/L), indicating a significant load of organic and inorganic contaminants. Biochemical oxygen demand (BOD_5) values were lower, ranging from 9.80 to 20.40 mg/L (mean: 13.20 mg/L), suggesting relatively limited biodegradable organic matter.

Total organic carbon (TOC) concentrations varied widely between 248.00 and 918.45 mg/L (mean: 554.58 mg/L). The broad range and high standard deviation reflect substantial variability in organic content. Notably, TOC values were consistently higher than COD, which is atypical since COD usually exceeds TOC in most wastewaters. This discrepancy can be attributed to refractory and aromatic hydrocarbons that contribute strongly to TOC but are not fully oxidized during dichromate COD analysis (Wojnárovits et al., 2024; Liao et al., 2023). High salinity and the complex hydrocarbon matrix may further inhibit COD oxidation, whereas TOC combustion captures all carbon, including refractory fractions (Wojnárovits et al., 2024).

Phenol concentrations ranged from 2.70 to 4.12 mg/L (mean: 3.40 mg/L), confirming the presence of toxic organic compounds requiring effective treatment. The combined concentration of BTEX (benzene, toluene, ethylbenzene, xylene) was relatively low, ranging from 2.77 to 7.00 mg/L (mean: 4.79 mg/L). Polycyclic aromatic hydrocarbons (PAHs) were also detected at 0.20–1.20 mg/L (mean: 0.56 mg/L), indicating low to moderate levels of these persistent pollutants.

Table 2
Statistical results of the physicochemical characteristics of the analysed produced water.

	Mean	Min	Max	25th Percentile	50th Percentile	75th Percentile
pH	6.4 ± 1.1	4.8	8.2	5.5	6.3	7.1
Conductivity [mS/cm]	28 ± 3	24.8	32.7	25.4	28.7	30.6
DO [mg/L]	4.3 ± 0.6	3.1	5.5	3.8	4.2	4.8
Turbidity [NTU]	140 ± 84	29.0	276.5	50.7	148.9	204.1
Alkalinity [mg/L $CaCO_3$]	325 ± 169	81.0	577.0	168.1	335.2	478.9
TDS [mg/L]	14 256 ± 1376	11 948	16 582	13 242	14 117	15398
TSS [mg/L]	346 ± 55	314.0	502.8	314.0	314.0	351.5
COD [mg/L]	471 ± 49	394.0	526.0	423.3	466.2	526.0
BOD_5 [mg/L]	13.2 ± 3.9	9.8	20.4	9.8	11.1	16.3
Phenol [mg/L]	3.4 ± 0.4	2.7	4.1	3.1	3.3	3.8
BTEX [mg/L]	4.8 ± 1.4	2.8	7.0	3.6	4.4	5.9
PAH [mg/L]	0.56 ± 0.35	0.2	1.2	0.2	0.56	0.91
TOC [mg/L]	555 ± 200	248.0	918.5	415.2	577.4	678.6
DOC [mg/L]	526 ± 201	210.0	863.6	362.9	475.9	697.7
TOG [mg/L]	96 ± 71	19.0	206.7	19.0	111.7	160.5
TPH [mg/L]	54 ± 28	12.0	105.0	27.2	55.3	75.4

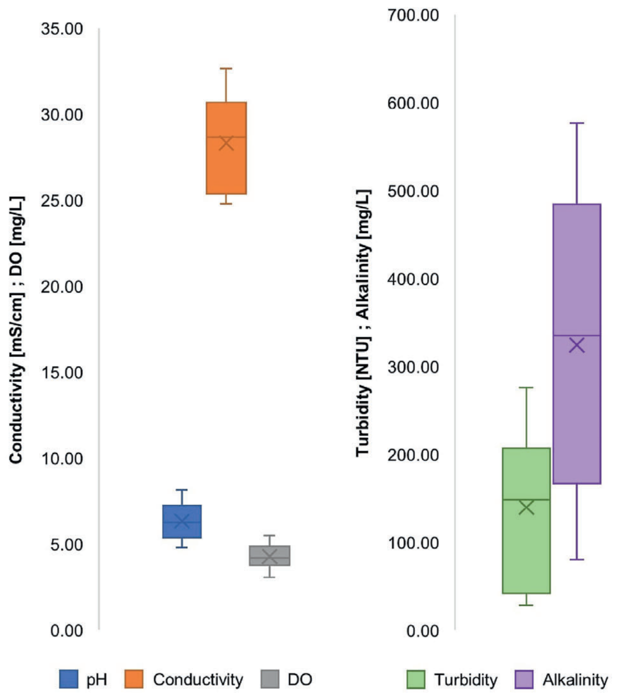

Fig. 2. Results of pH, conductivity, dissolved oxygen, turbidity and alkalinity analysis of the produced water.

Fig. 4 represents the distribution of total oil and grease (TOG) and total petroleum hydrocarbons (TPH) concentrations in the produced water with respective trends observed for the set of samples analysed in the form of a scatter plot. Light and dark shades indicate areas with lower and higher densities, respectively. For TOG (average: 96.08 mg/L), the distribution indicates two distinct groups within the data, with one group clustered at a low value of 19.00 mg/L and the second group spread out across higher values. The distribution of TPH is more uniform compared to TOG, with a central tendency around the average value of 54.04 mg/L. The Pearson correlation analysis ($r = -0.03$, $p = 0.849$) between TOG and TPH suggests no statistically significant linear relationship, indicating that these two variables behave independently in Angola's produced water. This unexpected result raises critical questions about hydrocarbon speciation and why TOG and TPH do not correlate as expected. One possible explanation lies in fractional composition differences, as TOG encompasses both non-polar and polar hydrocarbons, while TPH quantifies only non-polar fractions, excluding oxygenated hydrocarbons such as acids and alcohols, which may be prevalent in Angola's produced water. Another contributing factor could be oil-water emulsions, where poorly dispersed oil droplets are captured in TOG analysis but may not be fully extracted in TPH measurements, particularly if emulsifiers influence the TOG-to-TPH ratio. Additionally, operational conditions such as hydrocyclone efficiency and separation performance may play a role, with small, stabilized oil droplets persisting in TOG while heavier hydrocarbons are effectively removed, reducing TPH concentrations (ASTM International, 2022).

To contextualize the findings within a broader scope, a comparative analysis was performed using data from offshore oilfields worldwide. The results, illustrated in Fig. 5 as a Principal Component Analysis (PCA) biplot, provide insights into the relationships between key water quality parameters. Due to data availability constraints, the analysis was limited to Phenol, COD, BTEX, PAHs, TDS, and Oil and Grease.

The PCA reduced the dataset into two principal components, with PC1 (36.31%) and PC2 (26.33%) together explaining 62.64% of the total variance. This dimensionality reduction effectively captured dominant compositional trends across regions. Clusters on the biplot indicate shared characteristics: The North Sea and Permian Basin grouped closely, reflecting their salinity-dominant profiles, whereas India and Qatar diverged significantly. Angola occupied an intermediate position, suggesting its produced water shares traits with multiple regions while retaining unique features.

Table 3 further benchmarks Angola's offshore Block 15 against selected oil-producing regions. The produced water was moderately saline (TDS 14 256 mg/L), far lower than the North Sea (>200 000 mg/L) and the Permian Basin (128 000 mg/L), but comparable to Nigeria and Brazil. However, oil and grease concentrations (96 mg/L) and total petroleum hydrocarbons (54 mg/L) were among the highest reported globally, placing Angola alongside hydrocarbon-rich regions such as the Permian Basin and China. Organic contaminants including BTEX (4.8 mg/L), PAHs (0.56 mg/L), and phenols (3.4 mg/L) fell within global ranges, though phenol concentrations were slightly elevated. A distinguishing feature of Angola's produced water was the exceptionally high nickel concentration (average 314 mg/L), which far exceeded values reported in other regions and likely reflects corrosion of nickel-based alloys in production systems.

3.3. Biodegradability assessment

The organic strength of wastewater is commonly assessed using COD and BOD_5. COD measures the total organic matter

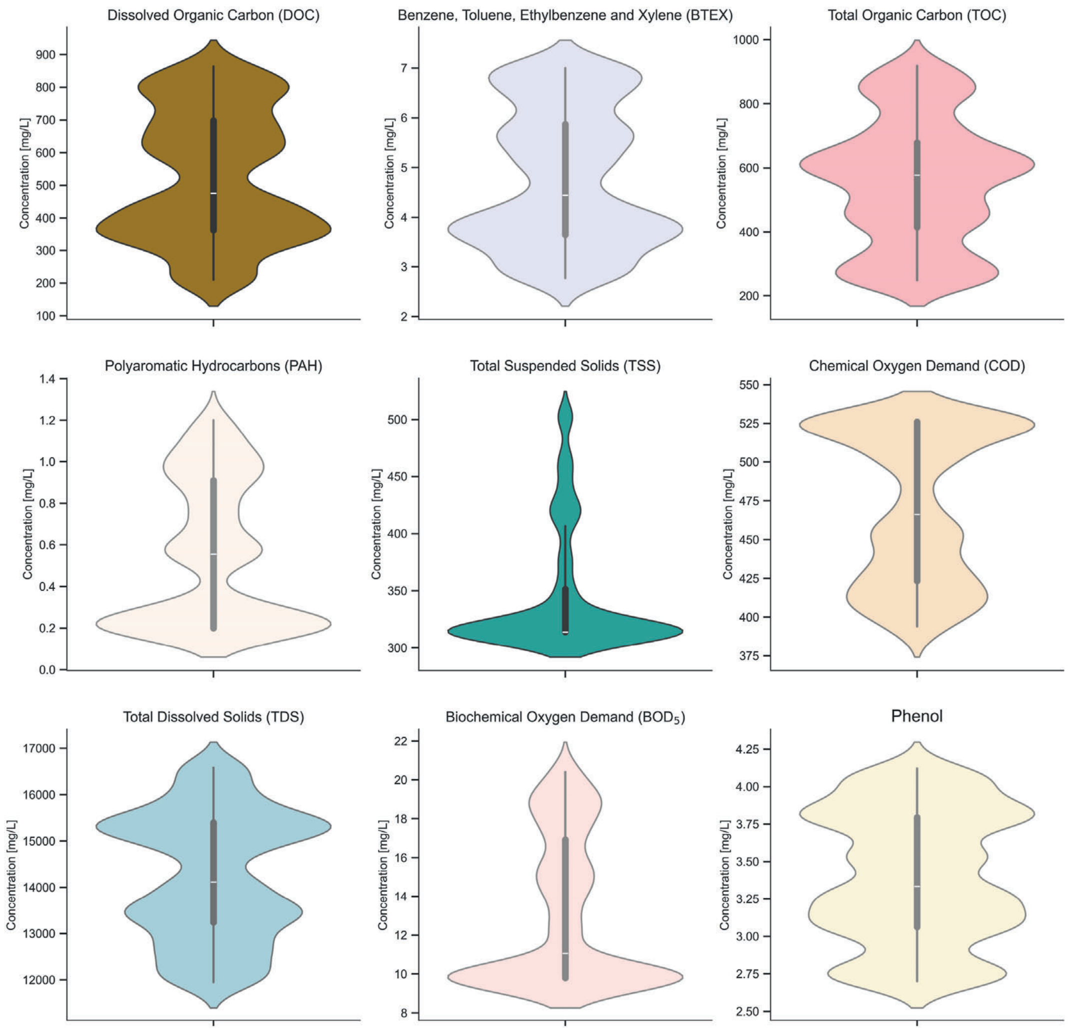

Fig. 3. Results of TDS, TSS, COD, BOD_5, phenol, PAH, BTEX, TOC and DOC analysis of the produced water.

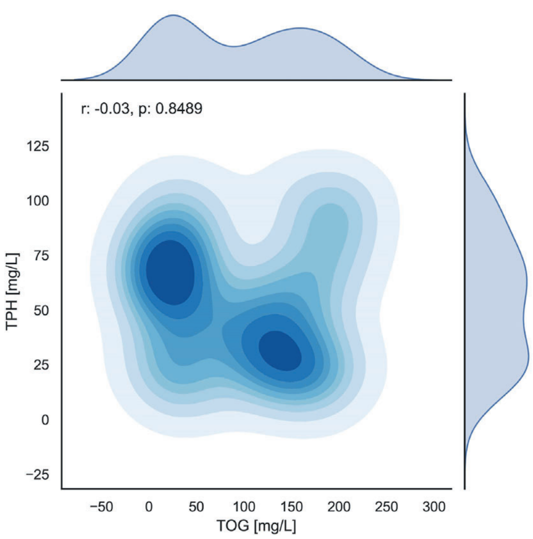

Fig. 4. Density plot of TOG vs TPH.

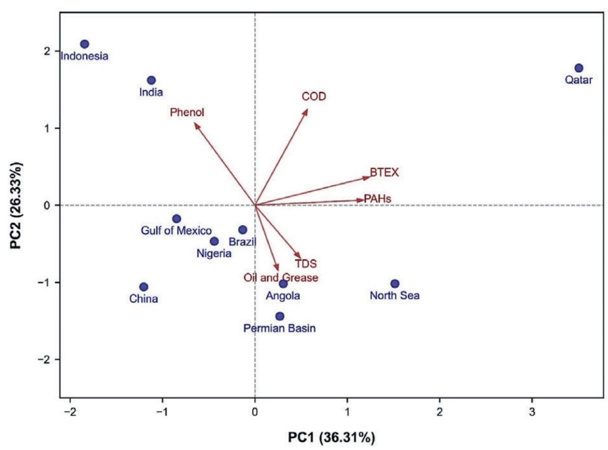

Fig. 5. Principal component analysis (PCA) of produced water composition (Amakiri et al., 2023; Ahan, 2014; Al-Kaabi et al., 2019; Amakiri et al., 2022; Dórea et al., 2007; Effendi et al., 2022; Eldos et al., 2022; Fillo et al., 1992; Gabardo et al., 2011; Gul Zaman et al., 2021; Herawati et al., 2023; Hu et al., 2022; Janson et al., 2015; Ji et al., 2002; Jiang et al., 2022; Kumar et al., 2022; Lahlou et al., 2020; Lu et al., 2006; Neff et al., 2011; Pampanin and Sydnes, 2013; Suzuki and Alhadeff, 2022).

Table 3
Comparative produced water composition: Angola versus other oil-producing regions (Amakiri et al., 2023; Ahan, 2014; Al-Kaabi et al., 2019; Amakiri et al., 2022; Dórea et al., 2007; Effendi et al., 2022; Eldos et al., 2022; Fillo et al., 1992; Gabardo et al., 2011; Gul Zaman et al., 2021; Herawati et al., 2023; Hu et al., 2022; Janson et al., 2015; Ji et al., 2002; Jiang et al., 2022; Kumar et al., 2022; Lahlou et al., 2020; Lu et al., 2006; Neff et al., 2011; Pampanin and Sydnes, 2013; Suzuki and Alhadeff, 2022).

Region	COD (mg/L)	BTEX (mg/L)	PAHs (mg/L)	Phenol (mg/L)	TOG (mg/L)	TDS (mg/L)
Angola	394–526	2.8–7.0	0.2–1.2	2.7–4.1	19–206	11 948–16 582
Nigeria	320–580	1.5–6.2	0.15–1.0	1.5–3.8	25–190	10 200–25 400
Brazil	400–700	0.5–4.5	0.10–0.8	1.0–2.5	40–160	15 000–35 000
Qatar	300–600	2.0–6.5	0.20–1.0	2.0–4.2	30–210	18 000–28 000
Permian Basin	350–800	1.8–5.4	0.2–0.9	1.2–3.6	60–160	50 000–128 641
North Sea	400–700	0.9–5.0	0.3–1.2	1.5–3.2	80–180	100 000–229 860
India	350–600	2.0–5.0	0.2–1.0	–	50–150	20 000–45 000
China	280–540	1.0–4.0	0.15–0.9	1.0–2.8	35–120	15 000–30 000
Indonesia	400–650	–	0.2–0.7	2.0–4.0	–	18 000–32 000
Gulf of Mexico	300–550	1.2–4.8	0.2–1.0	1.5–3.0	40–140	25 000–60 000

concentration in the water, while BOD_5 evaluates the biodegradable portion of such organic matter. The biodegradability index (BOD_5 to COD ratio) indicates how readily organic pollutants can be broken down biologically. A ratio greater than 0.6 suggests high biodegradability, between 0.3 and 0.6 indicates moderate biodegradability, and less than 0.3 implies low biodegradability with a significant amount of non-biodegradable matter present (Lacalamita et al., 2024; Choi et al., 2017; Henze et al., 2002). Due to the empirical correlation between BOD_5 and COD, COD measurements can be used to approximate BOD_5 values for a given sample, although this correlation is specific to each site (Henze et al., 2002). COD testing is advantageous because it delivers rapid results, unlike the five-day BOD_5 test, which only offers retrospective data due to the length of time required to obtain results and does not facilitate rapid water quality assessment for optimal process control (Abdalla and Hammam, 2014; Henze et al., 2002). The relationship between Influent BOD_5 and COD of the produced water stream exiting the three-phase separator is depicted in a comprehensive pair plot (Fig. 6). This plot includes kernel density estimates (KDE) for both BOD_5 (Fig. 6A) and COD (Fig. 6D), a contour plot overlaid on a scatter plot displaying the Pearson correlation coefficient and p-value (Fig. 6C) and a scatter plot with a fitted polynomial regression (Fig. 6B).

The KDE plots reveal that BOD_5 values clustered around 10–18 mg/L, while COD values concentrated around 450–520 mg/L, indicating a bimodal distribution for both parameters. A strong positive correlation ($r = 0.91$) between BOD_5 and COD is evident, with a statistically significant p-value of 0.00, implying that as COD increases, BOD_5 also tends to rise. The quadratic polynomial trendline emerged as the best fit, with an R^2 value of 0.95, suggesting that the relationship, while not perfectly linear, can be well represented by a quadratic function. This polynomial model accounts for 95% of the variance in BOD_5 values based on COD.

Fig. 7 illustrates the calculated biodegradability index for the produced water from Angola block 15, which yielded an average of 0.028 within the range of 0.021–0.039. The biodegradability index (0.028) of the produced water suggests that conventional biological treatment methods would be ineffective due to the high presence of refractory organics and toxic compounds. The presence of phenol (2.70–4.12 mg/L) further supports this limitation, as phenolic compounds are known to inhibit microbial activity, making biological degradation difficult (Abdalla and Hammam, 2014).

4. Environmental challenges and treatment strategies

Non-compliance with environmental discharge regulations can result in severe ecological consequences, including marine habitat contamination and disruptions to fisheries, underscoring the need for strict monitoring and enforcement. Angola's produced water composition, particularly its organic and inorganic pollutant load, differs from other offshore regions, necessitating site-specific treatment strategies rather than a universal approach. With a TDS concentration of 14 256 mg/L, Angola's produced water exhibits moderate salinity compared to the North Sea (229 860 mg/L) and the Permian Basin (128 641 mg/L). However, high chloride levels (400–2146.84 mg/L) disrupt marine osmoregulation, affecting survival and reproduction (Jiang et al., 2022). Elevated

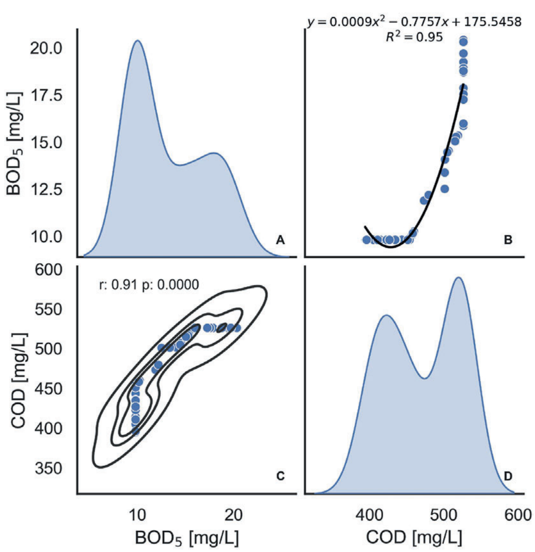

Fig. 6. Analysis of BOD_5 and COD correlation.

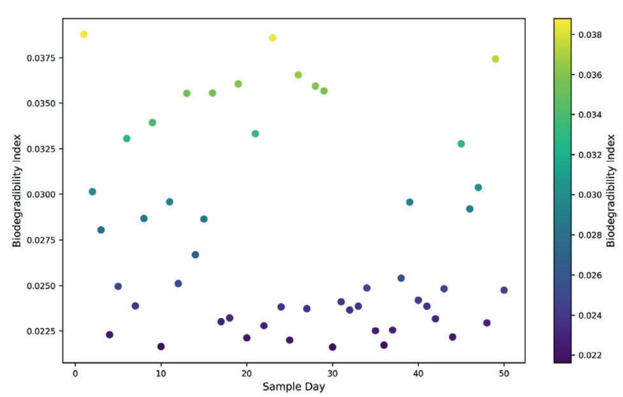

Fig. 7. Variation of Biodegradability Index Over 50 days.

TDS inhibits biological treatment efficiency due to osmotic stress, requiring desalination methods such as reverse osmosis or thermal distillation for reuse. Additionally, microbial sulfate reduction can generate hydrogen sulfide, increasing corrosion risks and necessitating sulfate removal technologies.

Hydrocarbon contamination remains a significant concern, with TOG (96.08 mg/L) exceeding Angola's discharge limit of 30 ppmw (César et al., 2024, 2025), posing risks of bioaccumulation, biodiversity loss, and food chain disruption (Hu et al., 2022). Mechanical separation via hydrocyclones and induced gas flotation is necessary before secondary treatments such as activated carbon adsorption or advanced oxidation to meet discharge standards. Persistent hydrocarbons (TPH: 54.04 mg/L) may require ozonation or Fenton's reagent for further degradation. Organic pollutants, including BTEX (4.79 mg/L) and PAHs (0.56 mg/L), present carcinogenic and mutagenic threats. PAHs persist in sediments, endangering benthic ecosystems (Hu et al., 2022), while a biodegradability index of 0.028 indicates resistance to natural degradation. Effective removal involves zeolite adsorption, membrane filtration, and advanced oxidation (Hayle, 2021).

Heavy metals such as nickel (314.07 mg/L) and iron (4.10 mg/L) further exacerbate environmental risks due to their bioaccumulation potential (Al-Ghouti et al., 2019). Often originating from production infrastructure corrosion, these metals highlight the need for corrosion-resistant materials and chemical inhibitors. Treatment methods such as chemical precipitation, ion exchange, and membrane separation are crucial for reducing metal concentrations before discharge.

High TSS (314.00–502.81 mg/L) and COD (394.02–526.00 mg/L) indicate substantial organic and inorganic contamination. Increased TSS reduces oxygen exchange, while elevated COD suggests oxidizable organic matter that can deplete oxygen in receiving waters (Zhou et al., 2018). Multimedia filtration and gas flotation effectively reduce TSS, while advanced oxidation and biological aerated bioreactors lower COD to acceptable levels. Phenol concentrations (2.70–4.12 mg/L), though lower than other organic pollutants, remain toxic to aquatic life (Al-Ghouti et al., 2019). Derived from extraction chemicals and hydrocarbon degradation, phenols can be removed through activated carbon adsorption, synthetic resins, or enzymatic laccase-based bioreactors.

5. Recommendation for future work

Since produced water from offshore oil and gas producing platforms is often discharged into the environment, it is essential to treat it properly to meet regulatory standards and prevent pollution. The study emphasizes the importance of characterizing petroleum effluents. The following recommendations are proposed to aid a broader characterization of produced water to determine the best wastewater management within the Angolan context as well as assist in planning optimal treatment practice:

(1) Extend the characterization of produced water to include platforms from other blocks from Angolan offshore waters and conduct studies beyond the initial 50-day period to understand the full variability in quality.
(2) Conduct further analysis of organic compounds, including gasoline, diesel, and oil range organics, to thoroughly understand their composition.
(3) Investigate the presence of naturally occurring radioactive material (NORM), such as Radium, Uranium, Thorium, Polonium, and Plutonium, due to the limited data on NORM in Angolan produced water.
(4) Characterize the role of organic contaminants in aquatic toxicity, particularly their interactions with salinity and heavy metals, using various ecotoxicological models.
(5) Explore beneficial reuse applications in Angola which is a water-scarce region, ensuring regulatory compliance and environmental sustainability.
(6) Optimize treatment efficiency through the integration of physicochemical and biological processes while developing region-specific discharge regulations that balance environmental protection with operational feasibility.
(7) Further hydrocarbon fractionation analysis to distinguish between non-polar, polar, and semi-volatile fractions, thereby clarifying the observed TOG-TPH relationship.
(8) Apply advanced characterization techniques such as Fluorescence Excitation–Emission Matrices (FEEM) and Liquid Chromatography–Organic Carbon Detection (LCOCD) to better profile the natural organic matter present in produced water.

6. Conclusion

This study provides an in-depth assessment of the produced water from Angola's offshore Block 15, highlighting its complex composition, which includes high salinity, hydrocarbons, organic contaminants, and heavy metals. The findings indicate that conventional biological treatment methods are inadequate due to the low biodegradability of wastewater, necessitating the use of advanced treatment techniques such as membrane separation, adsorption, and advanced oxidation processes.

Comparative analysis with produced water from other offshore oilfields suggests that while Angola shares some similarities with global counterparts, its unique characteristics require site-specific treatment strategies. Mechanical separation methods, such as hydrocyclones and induced gas flotation, are essential for oil and grease removal before secondary treatment. Additionally, the presence of persistent organic pollutants and heavy metals underscores the need for rigorous monitoring and regulatory compliance.

Given the lack of prior research on the produced water composition from Angolan offshore fields, this study serves as a foundational reference for future investigations. This study fills a critical knowledge gap in the characterization of Angola's produced water and serves as a foundation for further research. Future efforts should extend the analysis to other offshore blocks, explore additional organic and inorganic contaminants, and investigate potential reuse applications to support sustainable water management in the region.

CRediT authorship contribution statement

Sandro Duarte César: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Debbie De Jager:** Writing – review & editing, Validation, Supervision. **Mahomet Njoya:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors would like to express their gratitude to the various professionals who rendered any direct or indirect assistance to the work presented herein.

References

Abdalla, K., Hammam, G., 2014. Correlation between biochemical oxygen demand and chemical oxygen demand for various wastewater treatment plants in Egypt to obtain the biodegradability indices. Int. J. Sci. Basic Appl. Res. 13 (1), 42–48.

Ahan, J.A., 2014. *Characterization of Produced Water from Two Offshore Oil Fields in Qatar*. Master's Thesis. Qatar University.

Akinade, A., 2013. Analysis of formation water compositions and its effect on crude oil from off-shore location of Niger-Delta, Nigeria. Int. J. Sci. Res. 2 (11), 1–4.

AlAnezi, K., Al-Samhan, M., Belkharchouche, M., Abuhaimed, W., Alali, S., Alenizi, K., Alfuraij, A., 2018. Comparative analysis of produced water collected from different oil gathering centers in Kuwait. J. Environ. Protect. 9 (6), 736–750.

Al-Ghouti, M., Al-Kaabi, M., Ashfaq, M., Da'na, D., 2019. Produced water characteristics, treatment and reuse: a review. J. Water Proc. Eng. 28, 222–239.

Al-Kaabi, M., Al-Ghouti, M., Ashfaq, M.Y., Ahmed, T., Zouari, N., 2019. An integrated approach for produced water treatment using microemulsions modified activated carbon. J. Water Proc. Eng. 31, 00830.

Amakiri, K., Canon, A., Molinari, M., Angelis-Dimakis, A., 2022. Review of oilfield produced water treatment technologies. Chemosphere 298, 134064.

Amakiri, K., Ogolo, N., Angelis-Dimakis, A., Albert, O., 2023. Physicochemical assessment and treatment of produced water: a case study in Niger delta Nigeria. Petrol. Res. 8 (1), 87–95.

ANPG, 2019. Estratégia de Licitação 2019–2025. Luanda Agên. Nac. Petr. Gás Biocombust. (ANPG). Available at: https://anpg.co.ao/wp-content/uploads/2020/08/3371-DEZ-19-GIS-GAD-ESTRATEGIA-DE-LICITACAO-2019-2025_V1.pdf. (Accessed 21 October 2025).

ASTM International, 2022. ASTM D7678-17(2022) – Standard Test Method for Total Oil and Grease (TOG) and Total Petroleum Hydrocarbons (TPH) in Water and Wastewater with Solvent Extraction Using Mid-IR Laser Spectroscopy. ASTM International, West Conshohocken, PA.

César, S.D., 2022. Topside facilities' ability to handle a new blend of crude oil (Doctoral dissertation). Cape Penin. Univ. Technol.).

César, S.D., De Jager, D., Njoya, M., 2024. Environmental trade-offs in energy production: a review of the produced water life cycle and environmental footprint. Mar. Pollut. Bull. 203, 116480.

César, S.D., De Jager, D., Njoya, M., 2025. The role of hydrocyclone and induced gas flotation technologies in offshore produced water deoiling advancements. Petrol. Res. 10 (2), 342–351.

Chikwe, T., Okwa, F., 2016. Evaluation of the physico-chemical properties of produced water from oil producing well in the Niger Delta Area, Nigeria. J. Appl. Sci. Environ. Manag. 20 (4), 1113–1117.

Choi, Y., Baek, S., Kim, J., Choi, J., Hur, J., Lee, T., Park, C., Lee, B., 2017. Characteristics and biodegradability of wastewater organic matter in municipal wastewater treatment plants collecting domestic wastewater and industrial discharge. Water 9 (6), 409.

Dórea, H., Bispo, J., Aragão, K., Cunha, B., Navickiene, S., Alves, J., Romão, L., Garcia, C., 2007. Analysis of BTEX, PAHs and metals in the oilfield produced water in the State of Sergipe, Brazil. Microchem. J. 85 (2), 234–238.

Effendi, H., Mursalin, M., Hariyadi, S., 2022. Rapid water quality assessment as a quick response of oil spill incident in coastal area of Karawang, Indonesia. Front. Environ. Sci. 10, 757412.

Eldos, H., Khan, M., Zouari, N., Saeed, S., Al-Ghouti, M., 2022. Characterization and assessment of process water from oil and gas production: a case study of process wastewater in Qatar. Case Stud. Chem. Environ. Eng. 6, 100210.

Energy Institute, 2023. Statistical Review of World Energy 2023, 72nd Edition [Online]. Available from: https://www.energyinst.org/statistical-review/resources-and-data-downloads.

Fillo, J., Koraido, S., Evans, J.M., 1992. Sources, characteristics, and management of produced waters from natural gas production and storage operations. In: Ray, J. P., Engelhardt, F.R. (Eds.), Produced Water: Technological/Environmental Issues and Solutions. Springer, Boston, MA, US, pp. 151–161.

Gabardo, I., Platte, E., Araujo, A., Pulgatti, F., 2011. Evaluation of produced water from Brazilian offshore platforms. Prod. Water Environ. Risks Adv. Mitig. Technol. 89–113.

Gul Zaman, H., Baloo, L., Pendyala, R., Singa, P.K., Ilyas, S.U., Kutty, S.R.M., 2021. Produced water treatment with conventional adsorbents and MOF as an alternative: a review. Materials 14 (24), 7607.

Henze, M., Harremoes, P., Jansen, J., Arvin, E., 2002. Wastewater Treatment, Biological and Chemical Processes, third ed. Springer-Verlag, Berlin.

Herawati, N., Dahlan, M., Yusuf, M., Iqbal, M., Roni, K., Nasir, S., 2023. Removal of total dissolved solids from oil-field-produced water using ceramic adsorbents integrated with reverse osmosis. Mater. Today Proc. 87, 360–365.

Hu, L., Jiang, W., Xu, X., Wang, H., Carroll, K., Xu, P., Zhang, Y., 2022. Toxicological characterization of produced water from the Permian Basin. Sci. Total Environ. 815, 152943.

Janson, A., Santos, A., Katebah, M., Hussain, A., Minier-Matar, J., Judd, S., Adham, S., 2015. Assessing the biotreatability of produced water from a Qatari gas field. SPE J. 20 (5), 1113–1119.

Ji, G., Sun, T., Zhou, Q., Sui, X., Chang, S., Li, P., 2002. Constructed subsurface flow wetland for treating heavy oil-produced water of the Liaohe Oilfield in China. Ecol. Eng. 18 (4), 459–465.

Jiang, W., Xu, X., Hall, R., Zhang, Y., Carroll, K.C., Ramos, F., Engle, M., Lin, L., Wang, H., Sayer, M., Xu, P., 2022. Characterization of produced water and surrounding surface water in the Permian Basin, the United States. J. Hazard Mater. 430, 128409.

Jimenez, S., Mico, M., Arnaldos, M., Medina, F., Contreras, S., 2018. State of the art of produced water treatment. Chemosphere 192, 186–208.

Kumar, L., Chugh, M., Kumar, S., Kumar, K., Sharma, J., Bharadvaja, N., 2022. Remediation of petrorefinery wastewater contaminants: a review on physicochemical and bioremediation strategies. Process Saf. Environ. Prot. 159, 362–375.

Lacalamita, D., Mongioví, C., Crini, G., 2024. Chemical oxygen demand and biochemical oxygen demand analysis of discharge waters from laundry industry: monitoring, temporal variability, and biodegradability. Front. Environ. Sci. 12, 1387041.

Lahlou, F., Mackey, H., McKay, G., Onwusogh, U., Al-Ansari, T., 2020. Water planning framework for alfalfa fields using treated wastewater fertigation in Qatar: an energy-water-food nexus approach. Comput. Chem. Eng. 141, 106999.

Liao, D., Chen, Y., Yin, F., Lv, B., Wu, F., Xie, J., Feng, D., 2023. Performance of electrochemical treatment of refractory organic matter in printing and dyeing reverse osmosis concentrate. J. Environ. Chem. Eng. 11 (1), 109173.

Lu, J., Wang, X., Shan, B., Li, X., Wang, W., 2006. Analysis of chemical compositions contributable to chemical oxygen demand (COD) of oilfield produced water. Chemosphere 62 (2), 322–331.

Ma, F., Guo, J.B., Zhao, L.J., Chang, C.C., Cui, D., 2009. Application of bioaugmentation to improve the activated sludge system into the contact oxidation system treating petrochemical wastewater. Bioresour. Technol. 100 (2), 597–602.

Nasiri, M., Jafari, I., Parniankhoy, B., 2017. Oil and gas produced water management: a review of treatment technologies, challenges, and opportunities. Chem. Eng. Commun. 204 (8), 990–1005.

Neff, J., Lee, K., DeBlois, E., 2011. Produced water: overview of composition, fates, and effects. Prod. Water Environ. Risks Adv. Mitig. Technol. 3–54.

Olajire, A., 2020. Recent advances on the treatment technology of oil and gas produced water for sustainable energy industry-mechanistic aspects and process chemistry perspectives. Chem. Eng. J. Adv. 4, 100049.

Obunwo, C.C., Chukwudi, C., 2015. Assessment of physicochemical characteristics of produced water from terminals of some oil industry facilities in Nigeria. J. Appl. Sci. Environ. Manag. 19 (2), 177–180.

OPEC, 2023. OPEC Annual Statistical Bulletin. 58 th Edition. [Online]. Available from: https://asb.opec.org/ASB_Chapters.html

Pampanin, D.M., Sydnes, M.O., 2013. Polycyclic aromatic hydrocarbons a constituent of petroleum: presence and influence in the aquatic environment. Hydrocarbon 5, 83–118.

Razak, N.A., Mukhtar, H., Mohshim, D.F., 2022. Characterization of produced water from petroleum hydrocarbons terminal. J. Posit. School Psychol. 6 (3), 4415–4419.

Suzuki, R., Alhadeff, E., 2022. Improving the quality of produced water discharged in open waters by incorporating a microbiological treatment on operating offshore platforms: melhorar a qualidade da água produzida descartada em águas abertas, Incorp Rando um tratamento microbiológico nas plataformas offshore operacionais. Brazil. J. Develop. 8 (7), 54680–54699.

Wojnárovits, L., Homlok, R., Kovács, K., Tegze, A., Takács, E., 2024. Wastewater characterization: chemical oxygen demand or total organic carbon content measurement? Molecules 29 (2), 405.

Zheng, J., Chen, B., Thanyamanta, W., Hawboldt, K., Zhang, B., Liu, B., 2016. Offshore produced water management: a review of current practice and challenges in harsh/Arctic environments. Mar. Pollut. Bull. 104 (1–2), 7–19.

Zhou, Y., Duan, N., Wu, X., Fang, H., 2018. COD discharge limits for urban wastewater treatment plants in China based on statistical methods. Water 10 (6), 777.