Characterization of Produced Water from Hydrocarbon Terminals

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ABSTRACT

Produced water is the largest volume of waste generated during oil and gas production. It contains a complex mixture of organic and inorganic contaminants, including hydrocarbons, salts, and heavy metals, which pose significant risks to environmental and public health. This study focused on the characterization of produced water from three hydrocarbon terminals in the Niger Delta region of Nigeria. Samples were collected and analyzed to determine physical, chemical, and heavy metal parameters, including pH, turbidity, electrical conductivity, total dissolved solids (TDS), biological oxygen demand (BOD_5), chemical oxygen demand (COD), total oil and grease (TOG), and heavy metals such as lead, mercury, and cadmium. A freshwater sample was used as a control. Analytical methods included gravimetric analysis, titrimetric procedures, spectrophotometry, and atomic absorption spectroscopy. Statistical analysis, including ANOVA, was applied to evaluate spatial variations and significance across sample sites.

The findings revealed that while parameters like pH, TDS, EC, and salinity were within regulatory limits, others such as turbidity, COD, BOD_5, and TOG significantly exceeded permissible thresholds. Heavy metals including lead, zinc, barium, mercury, and cadmium were also found in concentrations far above acceptable limits, especially in Sample C. ANOVA results showed statistically significant differences among measured parameters but not among sampling locations, indicating consistent contamination across terminals. These findings emphasize the need for customized, multi-stage treatment systems to address diverse pollutant profiles. This study contributes to understanding produced water characteristics in Nigeria and supports regulatory compliance, treatment design, and improved environmental management strategies in the oil and gas sector.

Keywords: Produced water, hydrocarbon terminals, water quality, heavy metals, COD, BOD_5, TOG, environmental contamination, ANOVA, wastewater treatment, Niger Delta, regulatory compliance, oil and gas industry

INTRODUCTION

Produced water was one of the major waste streams generated during oil and gas extraction. It emerged from underground formations alongside crude oil or natural gas and often contained a complex mix of contaminants [18]. Hydrocarbon terminals, where crude oil was processed and stored, contributed significantly to this volume. Proper characterization of produced water remained essential for selecting effective treatment systems and reducing environmental impacts [7].

The composition of produced water varied widely depending on the geological source and operational conditions. It typically included organic pollutants like hydrocarbons and phenols, inorganic substances such as salts and heavy metals, and, at times, radioactive elements [2], [10]. These contaminants posed serious risks to both environmental and human health. If improperly managed, they could pollute surface and groundwater, degrade soil quality, and release volatile compounds into the air [6], [17].

To address these risks, detailed sampling and analysis were required. Techniques such as gas chromatography, mass spectrometry, and atomic absorption spectroscopy provided critical insights into the types and concentrations of pollutants present [19], [3]. This information supported the design of treatment systems that targeted specific contaminants. As environmental standards became stricter, proper water characterization

played an increasingly important role in achieving compliance with both local and international regulations [16], [9].

The consequences of discharging untreated produced water were far-reaching. Pollutants accumulated in ecosystems, harming aquatic life and disrupting natural cycles [14]. Groundwater contamination could also occur, making drinking water unsafe for nearby communities [15]. Beyond environmental concerns, poor handling practices increased financial liabilities and strained resources for remediation [1].

A range of treatment methods was used to reduce the levels of contaminants. Physical processes such as sedimentation and filtration helped remove suspended solids [4]. Chemical treatments like coagulation and precipitation addressed dissolved impurities, while biological systems used microorganisms to break down organic materials [13]. Advanced methods, including membrane filtration and reverse osmosis, were applied for high-level purification [5], [21]. Treatment systems were often customized based on the water's chemical makeup.

This study focused on the characterization of produced water from petroleum hydrocarbon terminals. It aimed to identify the main pollutants, evaluate their potential risks to human health and the environment, compare measured concentrations with regulatory standards such as those from WHO and NUPRC, and propose suitable treatment strategies. Through this work, the goal was to support better decision-making, reduce the environmental impact of produced water, and promote safer practices in the oil and gas industry [8], [20].

LITERATURE REVIEW

Produced water was the largest byproduct of oil and gas production. Its complex nature stemmed from the mix of hydrocarbons, dissolved salts, heavy metals, and organic matter it contained. The volume and characteristics of produced water depended on multiple factors, including the geology of the reservoir, the age of the well, and the type of extraction method used [10], [11]. As oil fields aged and production declined, water output increased. In some cases, oil-to-water ratios reached 1:12, meaning large volumes of water accompanied minimal hydrocarbon yields [8].

Characterization involved analyzing physical, chemical, and biological parameters. Physically, factors like TSS, turbidity, temperature, and conductivity were key to determining treatment needs. For example, Nasiri et al. observed conductivity levels ranging from 4,200 to 180,000 µS/cm [16], while Jiménez et al. reported TSS values up to 1000 mg/L [10]. Chemically, the water often had high salinity and contained heavy metals such as lead, barium, and mercury [2]. Organic pollutants such as BTEX compounds, oil, and grease added to the complexity [12]. These parameters are summarized in Table 1. Thorough characterization helped in understanding these variations, guiding the selection of treatment strategies and ensuring compliance with environmental discharge standards.

Table I. Typical Physical and Chemical Properties of Produced Water

Parameter	Reported Range	Source
Total Suspended Solids (TSS)	1.2 – 1000 mg/L	Jiménez et al., 2018
Total Dissolved Solids (TDS)	100 – 400,000 mg/L	Al-Ghouti et al., 2019
Conductivity	4,200 – 180,000 µS/cm	Nasiri et al., 2017
pH	4.3 – 10	Razak et al., 2022
COD	1220 – 2600 mg/L	Jiménez et al., 2018
BOD	50 – 2000 mg/L	Jiménez et al., 2018
TOG (Oil and Grease)	10 – 1000 mg/L	Nasiri et al., 2017
BTEX (VOCs)	0.39 – 35 mg/L	Lin et al., 2020

Environmental and Health Impacts

Produced water discharge had severe implications for both environmental systems and public health. In aquatic environments, it reduced water quality, harmed organisms, and disrupted entire ecosystems. Toxic substances

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like hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), and heavy metals accumulated in sediments and organisms. These contaminants caused mutations, reproductive failure, and reduced biodiversity [7]. Discharge into surface waters also increased turbidity, decreased oxygen levels, and weakened the photosynthetic ability of aquatic plants.

On land, accidental spills or poor containment led to soil contamination and damaged agricultural land. Vegetation wilted, soil fertility declined, and groundwater aquifers became polluted. These changes often persisted for years without proper remediation. The impacts extended to human health as well. People exposed to heavy metals in water faced risks such as kidney damage, liver dysfunction, respiratory problems, and cancer [17]. Children were particularly vulnerable to developmental issues from lead and mercury exposure. Common exposure routes included ingestion of polluted water, dermal contact, and inhalation of vapors or dust particles.

The major impacts of these contaminants are summarized in Table 2. Effective treatment and strong environmental policy were essential to reduce these risks and protect public health.

Table II Environmental and Human Health Impacts of Key Contaminants in Produced Water

Contaminant	Environmental Impact	Health Impact	Source
Lead (Pb)	Bioaccumulation in sediments	Neurotoxicity, kidney damage	Nzediegwu et al., 2021
Mercury (Hg)	Toxic to aquatic organisms	Cognitive dysfunction, developmental issues	Nzediegwu et al., 2021
Hydrocarbons	Reduces oxygen in water, harms aquatic life	Respiratory issues, skin irritation	Gazali et al., 2017
PAHs	Long-term sediment contamination	Potential carcinogenic effects	Gazali et al., 2017
Salts (TDS)	Soil salinization, freshwater disruption	Gastrointestinal irritation (at high exposure)	Eyankware et al., 2016

Treatment Technologies for Produced Water

A variety of technologies were used to treat produced water, each designed to target specific pollutants. Most treatment processes involved multiple stages to ensure removal of oil, solids, dissolved salts, and organics. Physical methods formed the first line of treatment. Gravity separation and hydrocyclones removed larger oil droplets and particulates. These systems often achieved up to 90% oil removal under optimal conditions [21], [13]. Secondary systems like induced gas flotation (IGF) and dissolved air flotation (DAF) targeted smaller particles and improved removal efficiency to over 93% when chemical coagulants were added [2].

Chemical treatments were used for dissolved pollutants. Precipitation techniques helped remove heavy metals, while oxidation processes such as UV/H_2O_2 broke down persistent organics [10], [18]. Electrocoagulation combined physical and chemical mechanisms for high COD and oil removal. Biological treatment, although limited by high salinity, was adapted using halotolerant microorganisms. Aerobic systems like membrane bioreactors (MBRs) and anaerobic processes like UASB reactors achieved up to 85% COD reduction [15], [14].

Tertiary and thermal treatments such as reverse osmosis (RO), mechanical vapor compression (MVC), and crystallization were applied for final polishing or zero-liquid discharge goals. These methods produced reusable water but came with higher energy and operational demands [5].

Challenges in Produced Water Treatment

Despite technological advances, several challenges continued to hinder effective treatment of produced water. One of the primary issues was the variability in produced water characteristics. Composition could differ greatly between wells and change over time, making it difficult to apply a one-size-fits-all approach [12]. High salinity and extreme pH levels further complicated biological treatment options, as many conventional microbes could not survive under such conditions.

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The presence of recalcitrant organic compounds also posed difficulties. Some organics resisted degradation by standard biological or chemical methods, requiring advanced oxidation or adsorption techniques. High total dissolved solids (TDS) levels led to membrane fouling and scaling in RO and thermal systems, increasing downtime and maintenance costs [3]. Systems required extensive pretreatment to remain efficient.

Energy consumption was another concern. Thermal processes and high-pressure membrane systems demanded substantial power, raising operational costs and affecting sustainability goals [5]. Moreover, the capital costs of installing such systems discouraged smaller facilities from investing in them.

Economic feasibility remained a limiting factor. Adaobi and Iledare emphasized that without proper techno-economic assessments, many facilities risked using inefficient or overly costly systems [1]. Addressing these challenges required continued research, tailored treatment strategies, and scalable solutions.

Discharge Limits and Regulatory Frameworks

Regulatory frameworks played a key role in setting boundaries for produced water discharge. These limits were designed to protect the environment and human health from the harmful effects of untreated or poorly treated effluents. In Nigeria, the allowable oil-in-water concentration was set at 40 ppm for offshore, 20 ppm for nearshore, and 10 ppm for onshore discharges [1]. These thresholds were based on the sensitivity of the discharge area and its proximity to drinking water sources or ecologically vulnerable zones.

Different types of limits were enforced, including concentration-based, load-based, and volume-based limits. Concentration-based limits ensured that pollutant levels in discharged water did not exceed set thresholds. Load-based limits focused on the total quantity of a substance discharged over time, while volume-based limits restricted the total volume of effluent released.

Agencies such as the Nigerian Upstream Petroleum Regulatory Commission (NUPRC), NIMASA, and NOSDRA were responsible for enforcement. These agencies conducted routine sampling, issued discharge permits, and required regular monitoring reports [18]. Failure to comply attracted penalties and could result in the suspension of operations. Regulatory oversight thus ensured that oil and gas operators maintained environmentally responsible practices.

MATERIALS AND METHOD

This study employed a combination of descriptive and analytical research methods to evaluate the quality of produced water from selected hydrocarbon terminals in the Niger Delta region of Nigeria. The descriptive component involved gathering detailed information about water samples from various terminal sites, focusing on their physical, chemical, and biological properties. These data were used to build a comprehensive profile of produced water quality under different environmental conditions. The analytical component applied statistical tools, particularly descriptive statistics and Analysis of Variance (ANOVA), to investigate spatial variations in pollutant levels and to assess the impact of location on water quality.

Sampling procedures followed standard environmental protocols, ensuring the accuracy and consistency of results. Laboratory analysis was carried out on all collected samples to determine key parameters including pH, turbidity, conductivity, TSS, TDS, BOD, COD, chloride, salinity, and the concentrations of heavy metals. The results were compared with regulatory benchmarks set by the Nigerian Upstream Petroleum Regulatory Commission (NUPRC). This methodology provided a clear framework for determining whether produced water discharges met environmental safety thresholds and helped identify which locations required improved wastewater management.

Study Points

The study was conducted across three hydrocarbon terminals located within the Niger Delta region of Nigeria. These sites were selected based on their activity levels, environmental exposure, and relevance to petroleum operations. The region is known for its extensive oil and gas production and associated environmental challenges. Each sample location was coded as A, B, and C to ensure clarity in data comparison.

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In addition to produced water samples, a freshwater sample was collected to serve as a control for comparative purposes. The selected sites varied in proximity to urban settlements and natural water bodies, providing insight into how geographic and operational factors influenced water quality. This multi-point approach enabled the study to capture a wide spectrum of pollutant characteristics and environmental impacts, offering a representative analysis of the broader region.

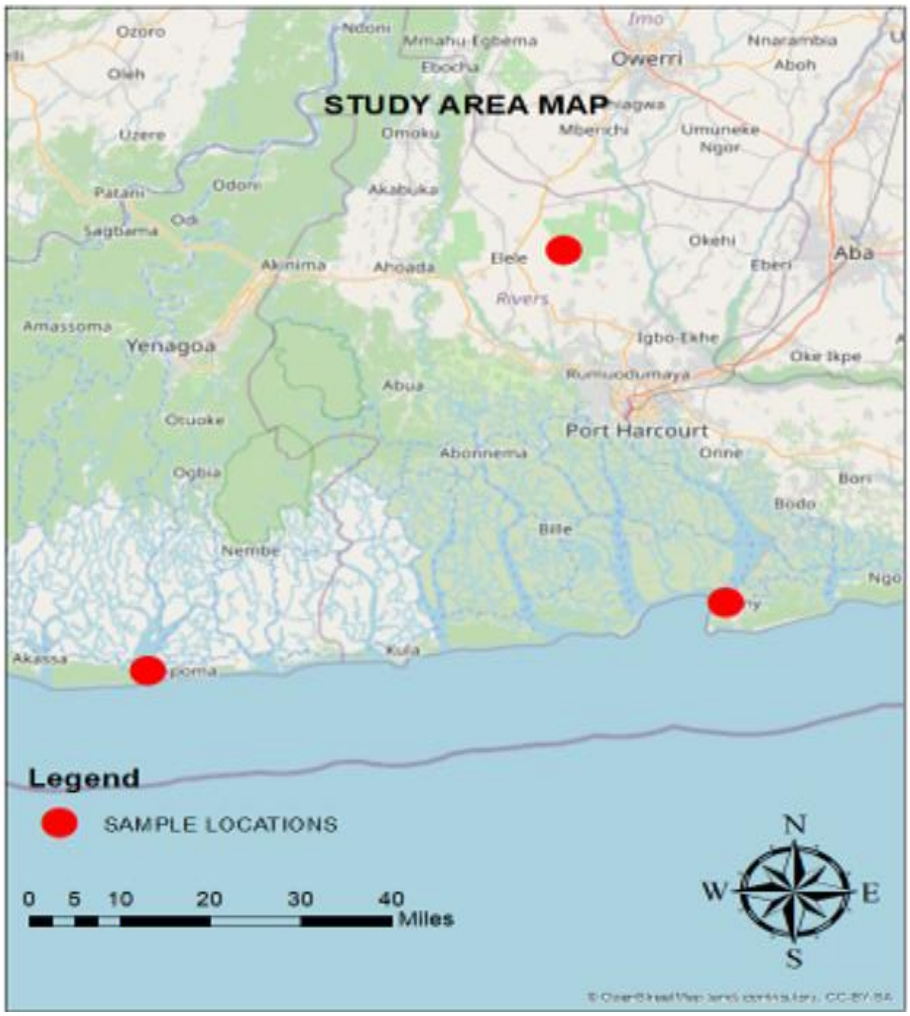

Fig. 1 Study area map of Niger-delta Region of Nigeria.

Materials

The materials used in this study were chosen to ensure sample integrity and accurate laboratory measurements. For field collection, amber glass bottles were used due to their resistance to UV light and chemical reactivity. Each bottle was rinsed with the sample water before final collection to minimize contamination. Samples were immediately stored in a cooler with ice blocks to preserve their physical and chemical properties during transportation.

Laboratory equipment included:

pH meter and thermometer for measuring hydrogen ion concentration and temperature.

Electrical Conductivity (EC) meter for ionic strength.

Turbidity meter (Hanna H198703) for particle analysis.

Evaporation dishes and desiccators for gravimetric analysis of salinity and TDS.

Burettes, pipettes, and conical flasks for titrations used in chloride, DO, and BOD analyses.

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Atomic Absorption Spectrophotometer (AAS) for the quantification of heavy metals.

UV-Visible spectrophotometer, where applicable, for COD measurement.

Chemical reagents used included potassium chloride, sodium chloride, silver nitrate, potassium chromate, and n-hexane. These ensured sensitivity and specificity during testing.

Method

The methodology adopted in this study was carefully designed to ensure reliable, reproducible, and valid results in characterizing produced water from hydrocarbon terminals. A step-by-step approach was followed, involving sample collection, preservation, laboratory analysis, and statistical evaluation. The procedures were guided by standard environmental sampling protocols and scientific best practices to maintain accuracy, eliminate bias, and reflect real environmental conditions.

Sample Collection and Preservation

Sampling was carried out at three hydrocarbon terminals within the Niger Delta region, each designated as Site A, B, and C. These terminals were selected due to their active crude oil handling operations and environmental sensitivity. One additional freshwater sample was collected to serve as a control or baseline.

Produced water samples were collected in 1-liter amber glass bottles. The amber glass prevented photodegradation of sensitive components like organic pollutants and trace metals. Each bottle was rinsed with the sample before collection to reduce external contamination. After collection, the bottles were sealed tightly, labeled, and placed in coolers containing ice blocks to preserve the chemical integrity of the samples. The samples were then transported to the laboratory within 24 hours to minimize alterations from biological or chemical processes.

Field Procedures

Sampling was conducted following recognized environmental monitoring protocols. Samples were obtained directly from discharge points or storage units at each terminal. Field notes were taken to record sample temperature, appearance (color, turbidity), and any odor. These physical observations provided initial indications of pollution and were useful for cross-checking laboratory results.

Three replicate samples were collected per site to allow for statistical comparison and to reduce variability. Care was taken to avoid contact with any metallic surfaces or contaminated tools during sampling. All instruments used were pre-sterilized and handled with gloves to prevent contamination.

Laboratory Procedures

In the laboratory, each sample was subjected to detailed physical, chemical, and biological analysis. Tests were conducted under controlled conditions, using standardized methods to ensure reproducibility. The procedures covered key water quality parameters, including pH, turbidity, electrical conductivity, temperature, salinity, total suspended solids (TSS), total dissolved solids (TDS), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), chloride, dissolved oxygen (DO), density, total oil and grease (TOG), and heavy metals such as lead, arsenic, iron, and manganese.

Data Analysis Carried Out

To ensure a comprehensive evaluation of water quality across the different terminal sites, several statistical tools and techniques were employed in this study. These included descriptive analysis, comparative analysis, and inferential statistics such as Analysis of Variance (ANOVA). All analyses were aimed at identifying trends, patterns, and significant differences in the quality of produced water from the three sampled locations. Microsoft Excel and SPSS were the primary tools used for data management, computation, and interpretation.

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Descriptive Statistical Analysis

Descriptive statistics were used as a first step in understanding the basic structure and behavior of the water quality data. These involved calculating the mean, standard deviation, and normalized values for each parameter measured at the three sampling locations (A, B, and C). Parameters analyzed included pH, turbidity, conductivity, total dissolved solids (TDS), total suspended solids (TSS), salinity, dissolved oxygen (DO), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), chloride, and concentrations of selected heavy metals.

Mean values provided insight into the average concentration or level of each parameter at the individual sites.

Standard deviations revealed the degree of variation or dispersion of the values from the mean, helping to evaluate the consistency or variability in pollution levels across the locations.

Normalization was applied to scale the values for better visual comparison and to reduce the effects of unit differences among parameters.

These calculations were tabulated and organized in Excel spreadsheets, allowing for clear interpretation and subsequent plotting of results.

Comparative Analysis

Comparative analysis was performed to assess the differences in water quality parameters across the three sample locations. By comparing values side-by-side, the analysis revealed whether certain locations exhibited significantly higher pollutant concentrations or whether the parameters fell within acceptable regulatory standards.

This analysis helped determine:

Which sites were most environmentally impacted.

Whether all measured parameters met the permissible discharge limits set by NUPRC or other international guidelines (e.g., WHO).

How each site compared to the freshwater control sample.

Bar charts and tables were generated to visually present this comparative data, making it easier to observe spatial trends and identify problematic sites.

Analysis of Variance (ANOVA)

To determine whether the observed differences between sampling sites were statistically significant, a two-way Analysis of Variance (ANOVA) was conducted using SPSS statistical software. The test was carried out at a 95% confidence level ($\alpha = 0.05$) to evaluate the effect of location (i.e., Site A, B, or C) on each water quality parameter.

The ANOVA procedure involved:

Grouping data by sampling site.

Comparing the means of each parameter between the groups.

Calculating the F-statistic to determine whether the variance between groups was greater than the variance within groups.

A p-value less than 0.05 indicated a statistically significant difference between sample sites for that parameter. The analysis revealed that several parameters—such as turbidity, TDS, BOD_5, COD, salinity, and heavy metals—varied significantly across the three locations. These findings confirmed that spatial variation was a key factor influencing produced water characteristics and helped in pinpointing areas with higher pollution intensity.

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Data Visualization

To enhance clarity and interpretation, results were visualized using:

Bar charts, showing parameter levels across sites.

Tables, summarizing statistical measures and ANOVA outputs.

Line plots, where applicable, to observe trends.

Visual tools supported quick comparison and made it easier to detect patterns, outliers, and deviations from expected norms.

Regulatory Comparison

Finally, the analyzed data were compared with regulatory standards, particularly those established by:

The Nigerian Upstream Petroleum Regulatory Commission (NUPRC),

World Health Organization (WHO), and

Federal Ministry of Environment (Nigeria).

Each parameter's value was checked against the relevant discharge limit or water quality guideline. This comparison determined the environmental compliance status of each terminal and identified which parameters exceeded safe limits.

RESULTS AND DISCUSSION

Comparation Of Produced Water Parameters With Fresh Water, Sea Water And Permissible Limit

The physical and chemical characteristics of produced water from three hydrocarbon terminals (Samples A, B, and C) were evaluated and compared against freshwater, seawater, and permissible regulatory limits. Parameters considered included pH, electrical conductivity (EC), total dissolved solids (TDS), salinity, turbidity, chloride, dissolved oxygen (DO), chemical oxygen demand (COD), biological oxygen demand (BOD_5), total oil and grease (TOG), and heavy metals. The full results are visually represented in Fig.s 1 to 21.

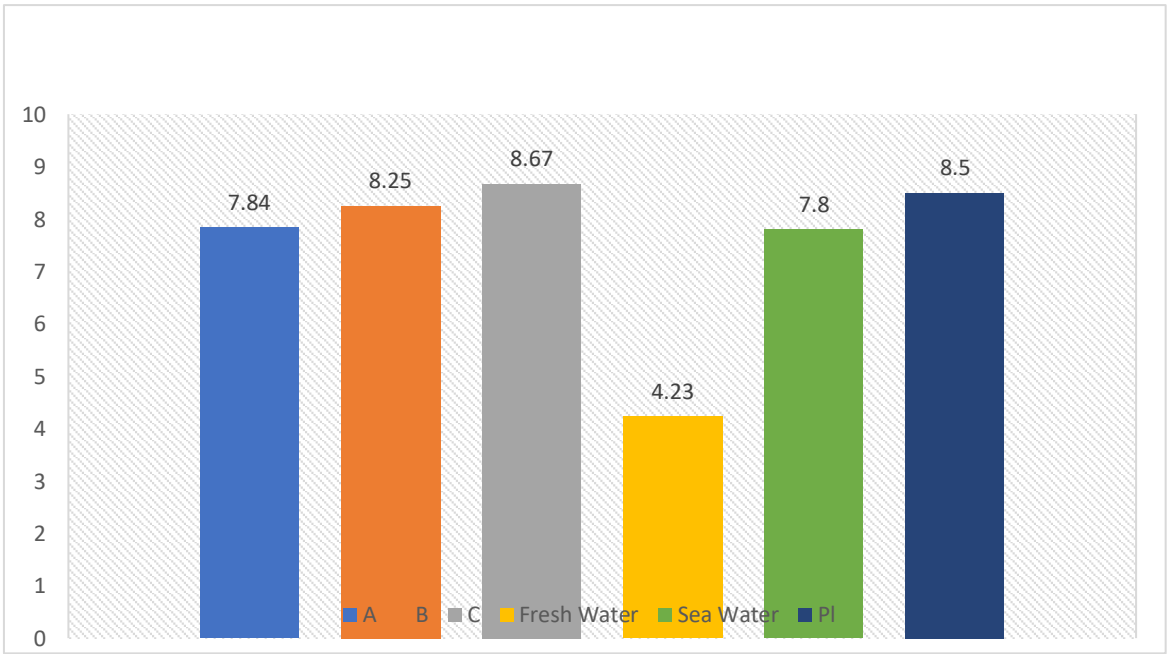

Fig. 1 pH values across samples

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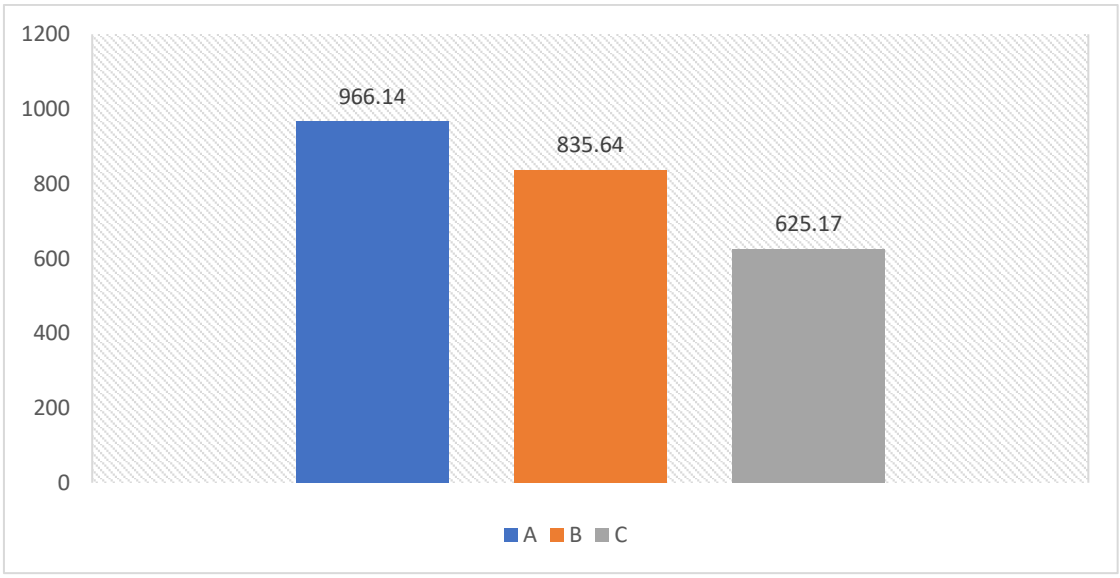

Fig. 2 EC values across samples

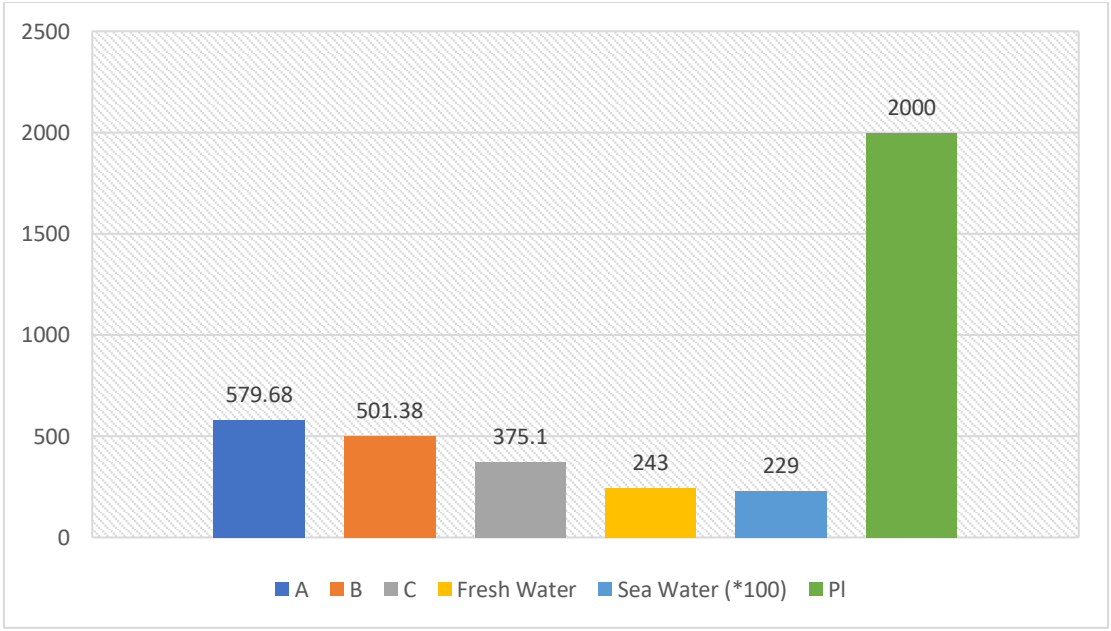

Fig. 3 TDS values across samples

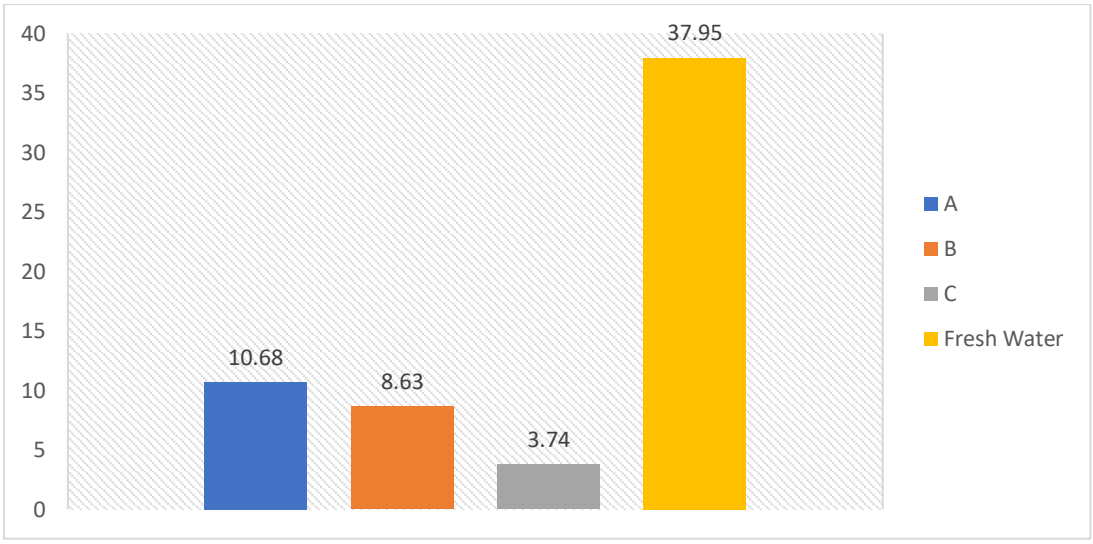

Fig. 4 salinity values across samples

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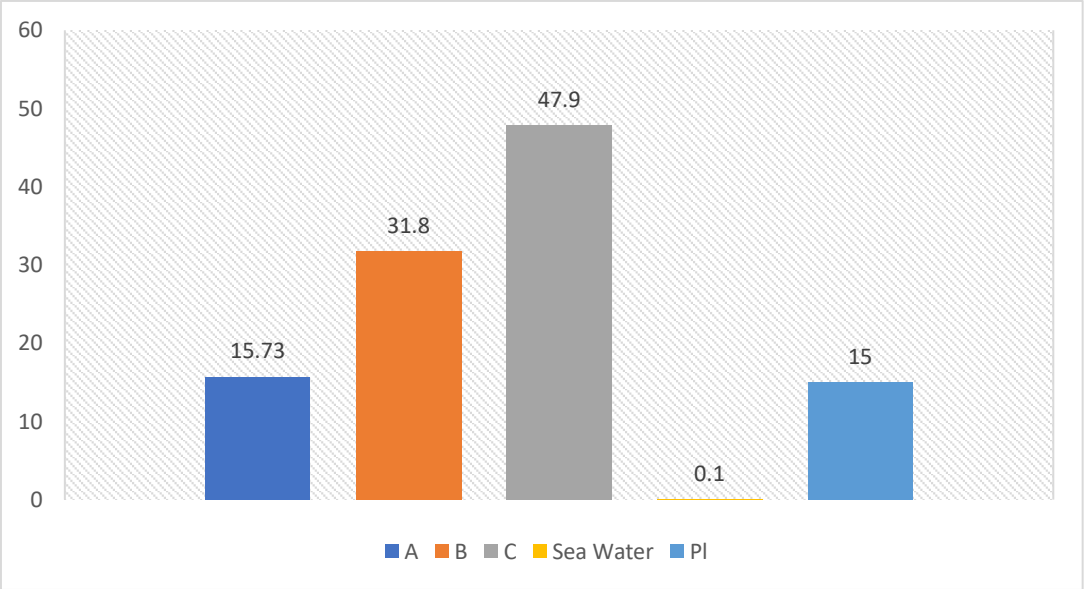

Fig. 5 Turbidity values across samples

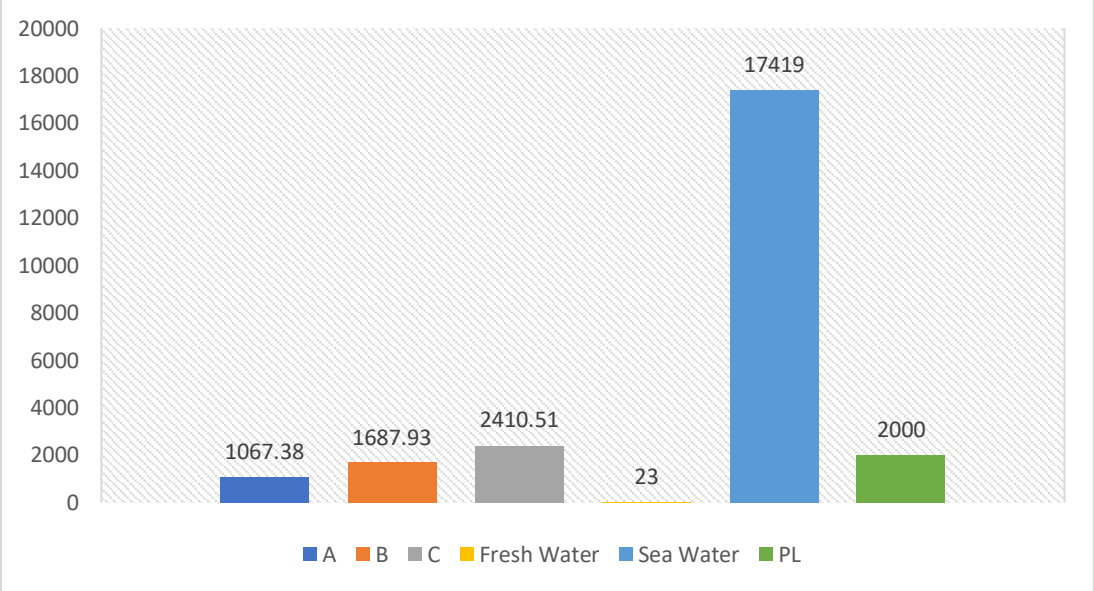

Fig. 6 Chloride values across samples

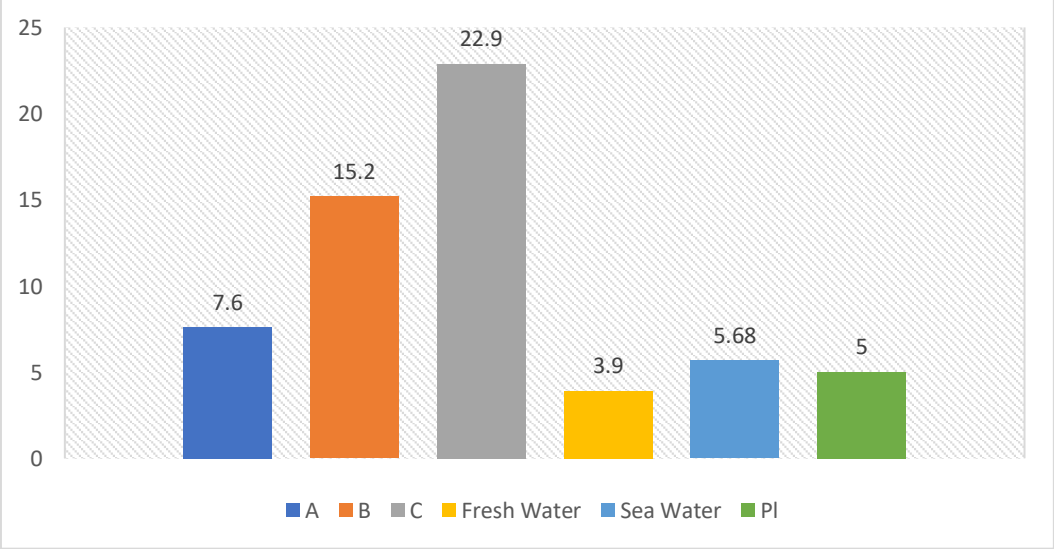

Fig. 7 DO values across samples

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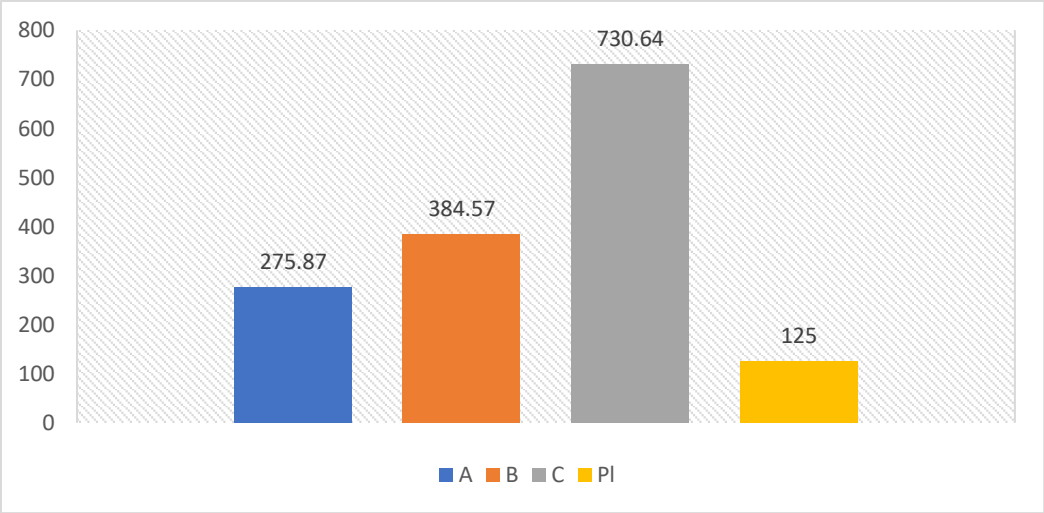

Fig. 8 COD values across samples

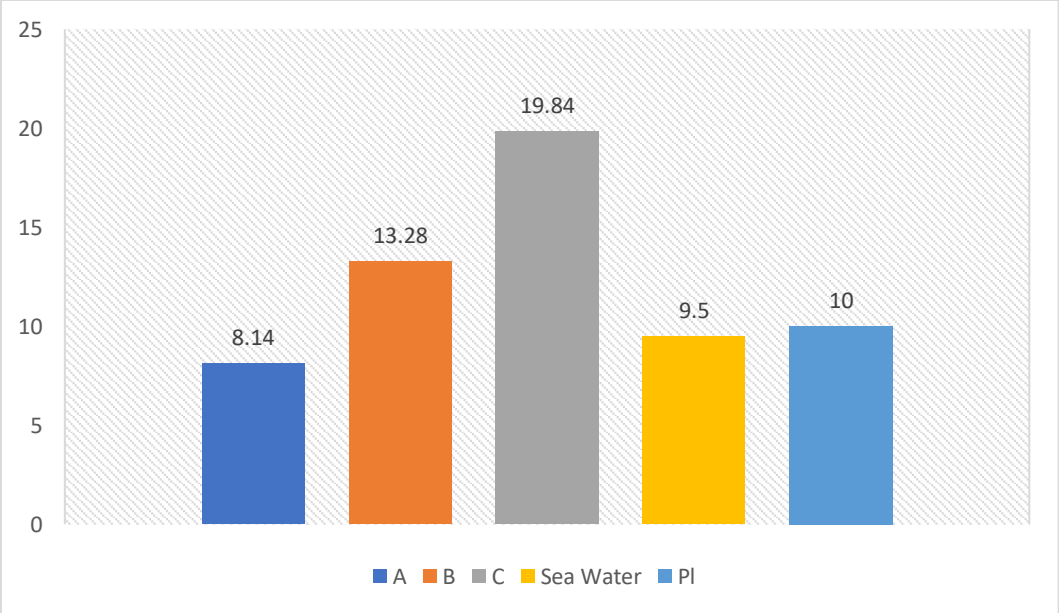

Fig. 9 BOD_5 values across samples

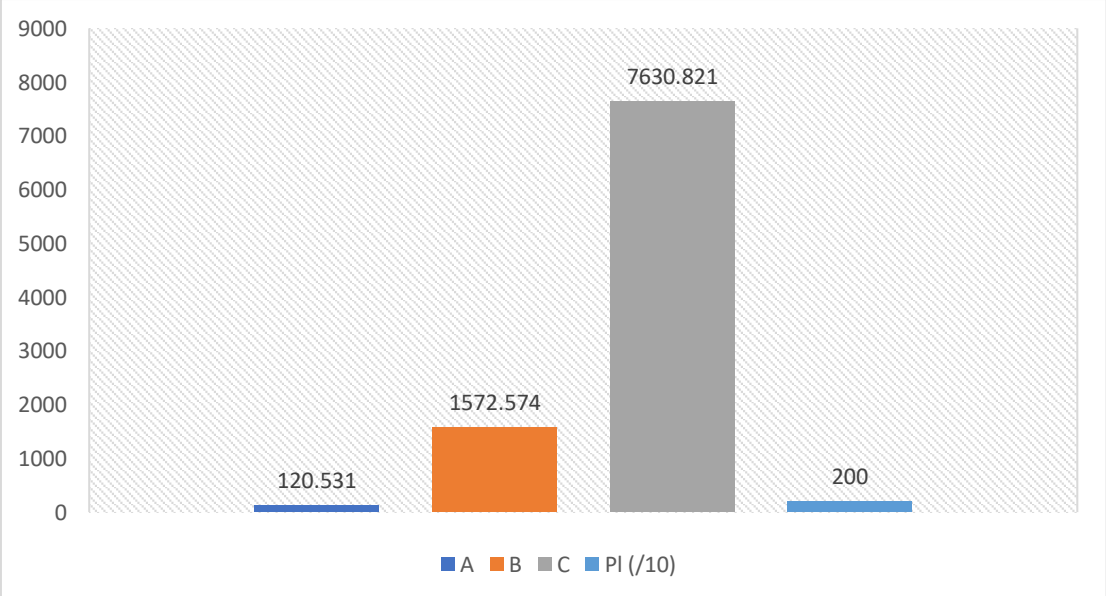

Fig. 10 TOG values across samples

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Starting with pH, all samples fell close to or within the WHO/NUPRC standard of 6.5 to 8.5, with Sample C registering a slightly alkaline value of 8.67 (Fig. 1). Although this value does not drastically exceed the limit, its proximity to the upper boundary suggests the possible presence of crude oil residues or alkali compounds. Sample A (7.84) and Sample B (8.25) were comfortably within the acceptable range. Similar trends were reported by Eyankware et al. in the Niger Delta, where pH values typically ranged from 8.1 to 8.9 [6].

Electrical conductivity values, depicted in Fig. 2, ranged from 685 µS/cm in Sample C to 1024 µS/cm in Sample A, indicating moderate mineralization. These values were higher than those of freshwater but significantly lower than those of seawater, suggesting the presence of ions such as chlorides, nitrates, and sulfates. This result aligns with the observations of Al-Ghouti et al. [2], who reported similar EC levels in untreated produced water.

TDS results (Fig. 3) showed a similar trend, with Sample A having the highest TDS (579.68 mg/L), followed by Sample B (501.38 mg/L) and Sample C (375.1 mg/L). These concentrations are well within the permissible limit of 1000 mg/L, indicating that the water, though moderately mineralized, is not excessively saline. Salinity values (Fig. 4) remained low across all samples, with Sample A recording 10.68 mg/L and Sample C the lowest at 3.74 mg/L. These values further support the idea of limited salt intrusion or formation water carryover.

In contrast, turbidity values, as shown in Fig. 5, exceeded the standard 5 NTU limit in all three samples. Sample C had the highest turbidity at 47.9 NTU, which may indicate the presence of dispersed oil droplets, particulate matter, or sampling from lower pipe depths. Turbidity values of this magnitude are known to interfere with aquatic photosynthesis and filter-feeding organisms, supporting similar conclusions by Nzediegwu et al. [17].

Chloride concentrations (Fig. 6) also varied across samples. While Samples A (1067.38 mg/L) and B (1687.93 mg/L) remained within the 2500 mg/L discharge limit, Sample C (2410.51 mg/L) approached the maximum allowable concentration. This trend could point to salinity intrusion or high chemical additive content, a scenario also reported by Nasiri et al. [16].

All three samples had elevated DO levels (Fig. 7), suggesting possible aeration during collection or low microbial activity. However, these high DO levels were insufficient to offset the extreme organic pollution observed. COD values, displayed in Fig. 8, far exceeded safe limits, with Sample C again topping the list. This indicates a substantial concentration of non-biodegradable organic pollutants, consistent with the findings of Al-Ghouti et al. [2], who reported COD levels above 2500 mg/L in untreated produced water.

The BOD_5 values (Fig. 9) were also problematic. Samples B (13.28 mg/L) and C (19.84 mg/L) surpassed the limit of 10 mg/L, suggesting the presence of readily biodegradable organic matter that would rapidly deplete oxygen in receiving waters. Only Sample A (8.14 mg/L) fell below the limit. Lusinier et al. similarly highlighted that untreated produced water often exhibits elevated BOD_5 due to oil degradation [14].

Lastly, TOG results (Fig. 10) were alarmingly high in Samples B (1572.574 mg/L) and C (7630.821 mg/L), with Sample A (120.531 mg/L) also exceeding limits. These values present serious ecological risks by forming films on water surfaces that impede oxygen exchange and light penetration. Dickhout et al. documented comparable values in offshore facilities, stressing the importance of advanced separation and treatment before discharge [5].

Comparison of Heavy Metals

This subsection presents the concentrations of key heavy metals found in the produced water samples and compares them to permissible limits. The metals analyzed include lead (Pb), zinc (Zn), magnesium (Mg), calcium (Ca), potassium (K), aluminum (Al), iron (Fe), sodium (Na), barium (Ba), mercury (Hg), and cadmium (Cd). Their concentrations across Samples A, B, and C are illustrated in Fig.s 11 to 21, which provide a clear view of variations between locations. Each Fig. highlights the presence and severity of contamination by individual metals, supporting the evaluation of environmental and health risks associated with the discharge of untreated produced water.

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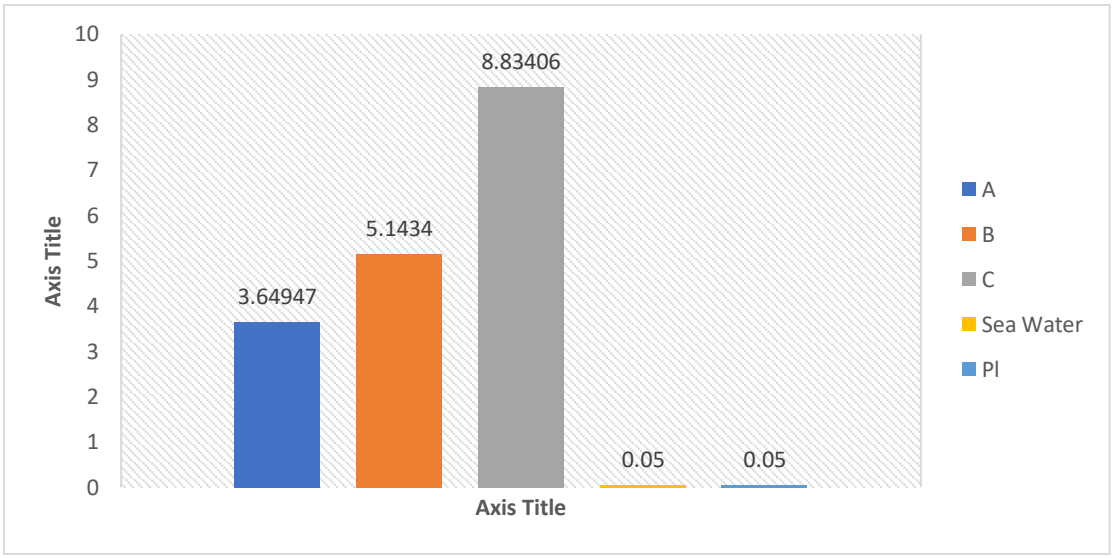

Fig. 11 Pb values across samples

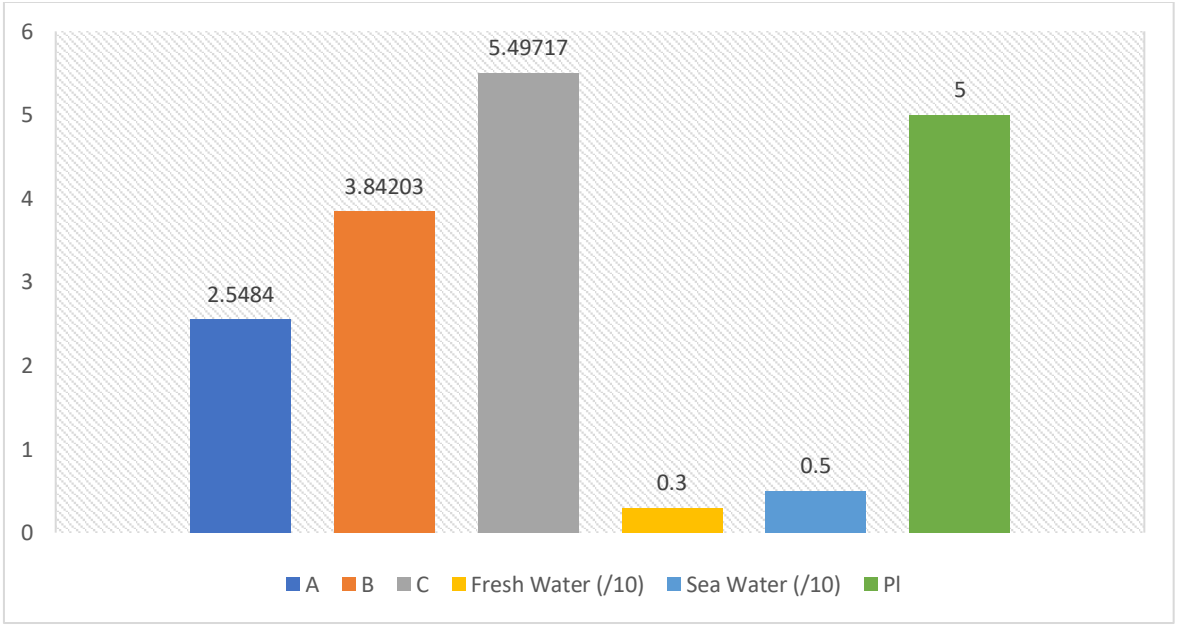

Fig. 12 Zn values across samples

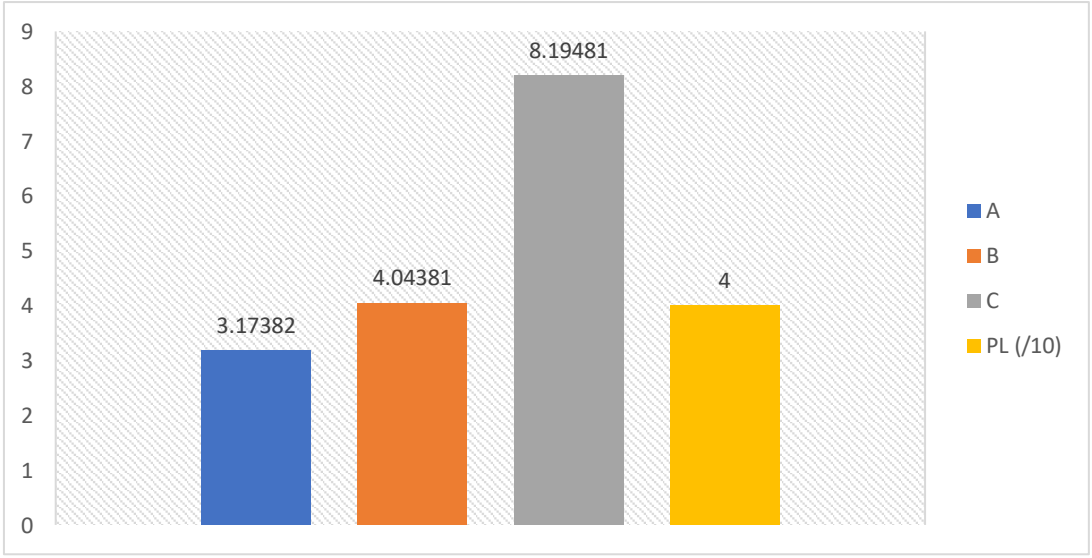

Fig. 13 Mg values across samples

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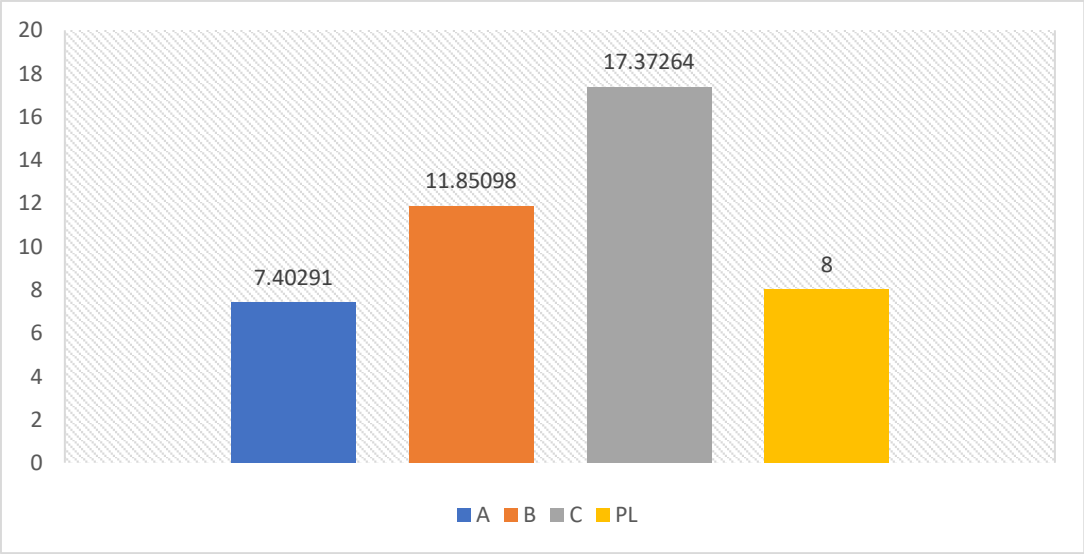

Fig. 14 Ca values across samples

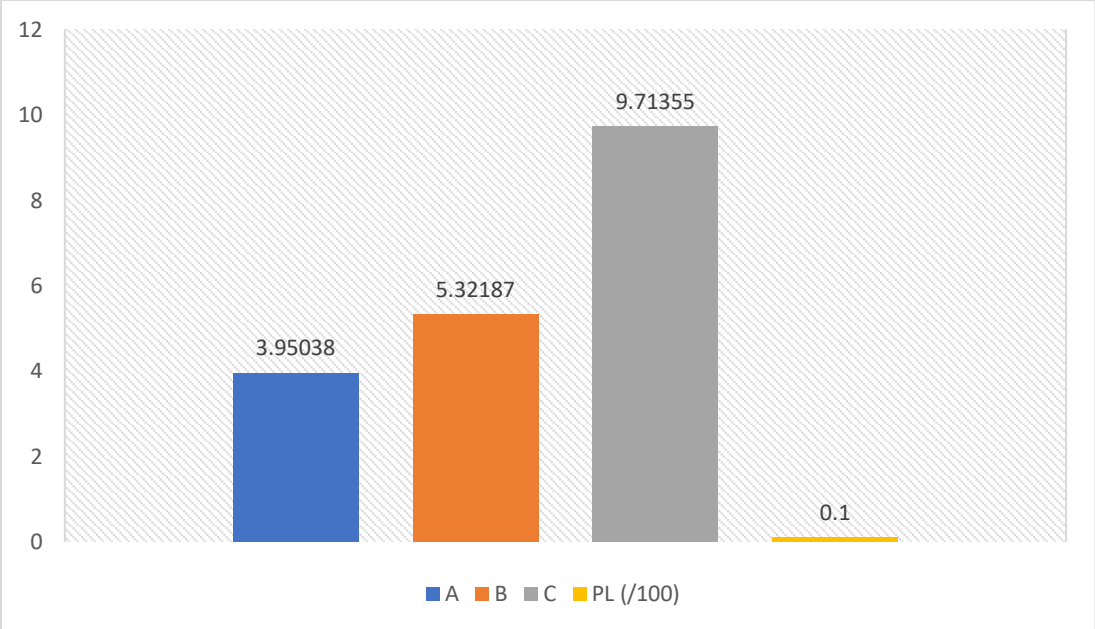

Fig. 15 A bar chart showing K values across samples

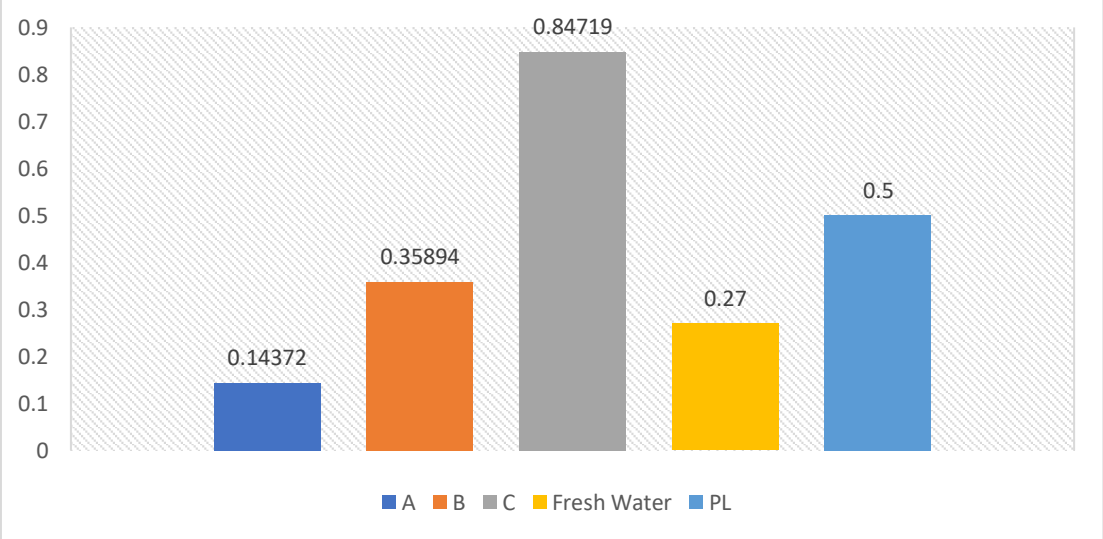

Fig. 16 Al values across samples

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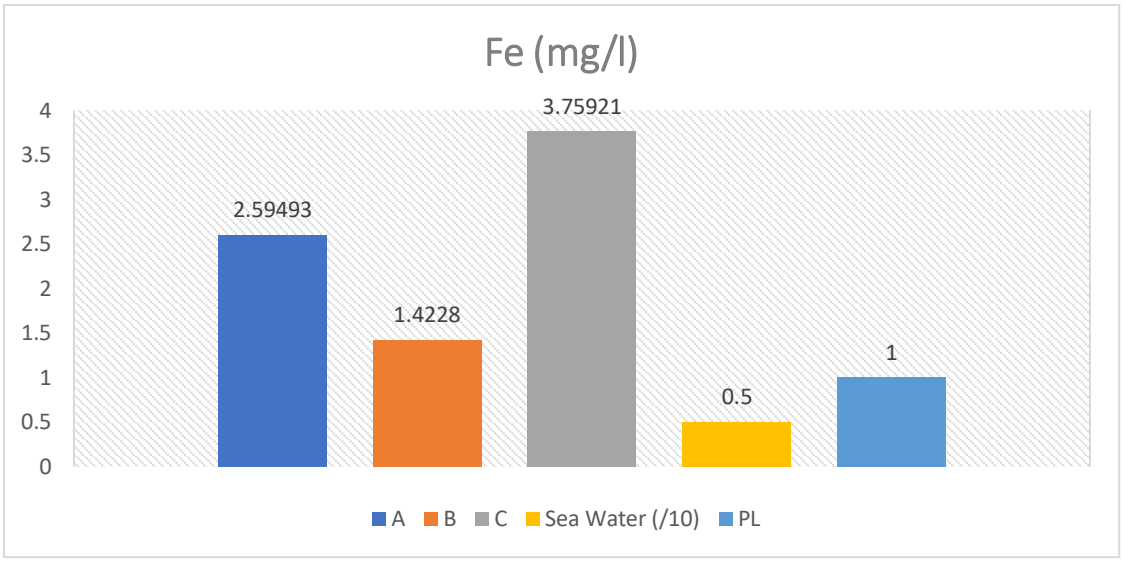

Fig. 17 Fe values across samples

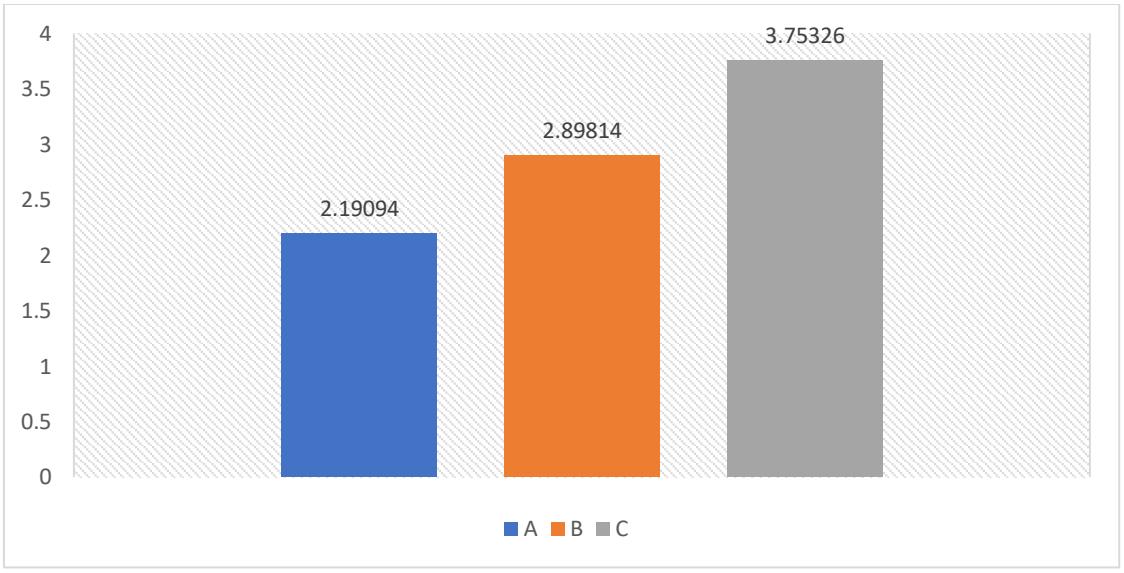

Fig. 18 Na values across samples

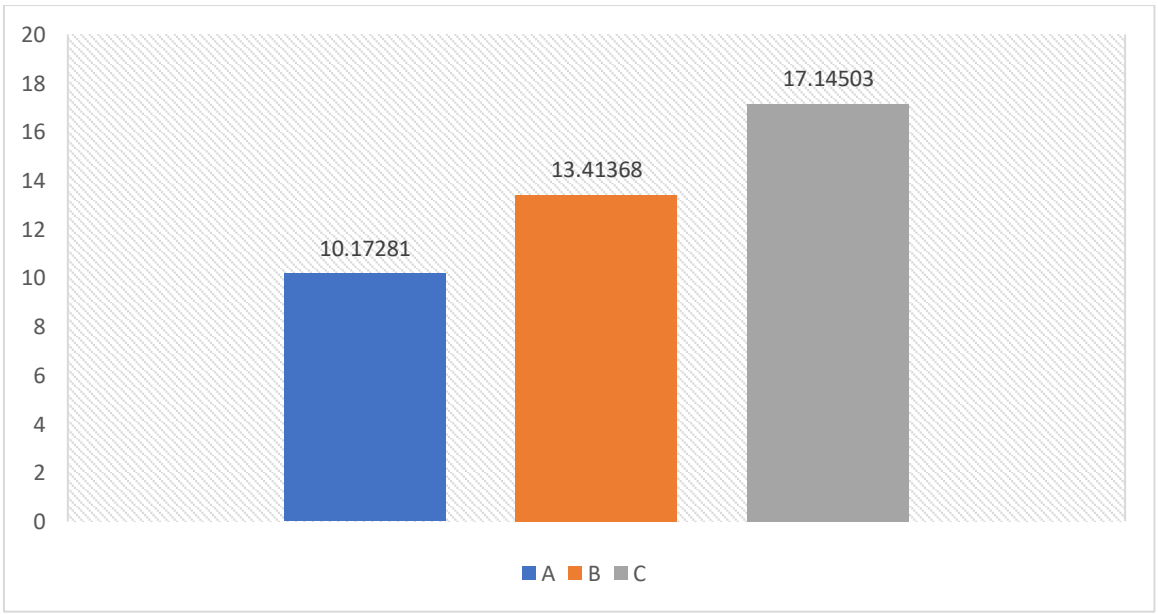

Fig. 19 A bar chart showing Ba values across samples

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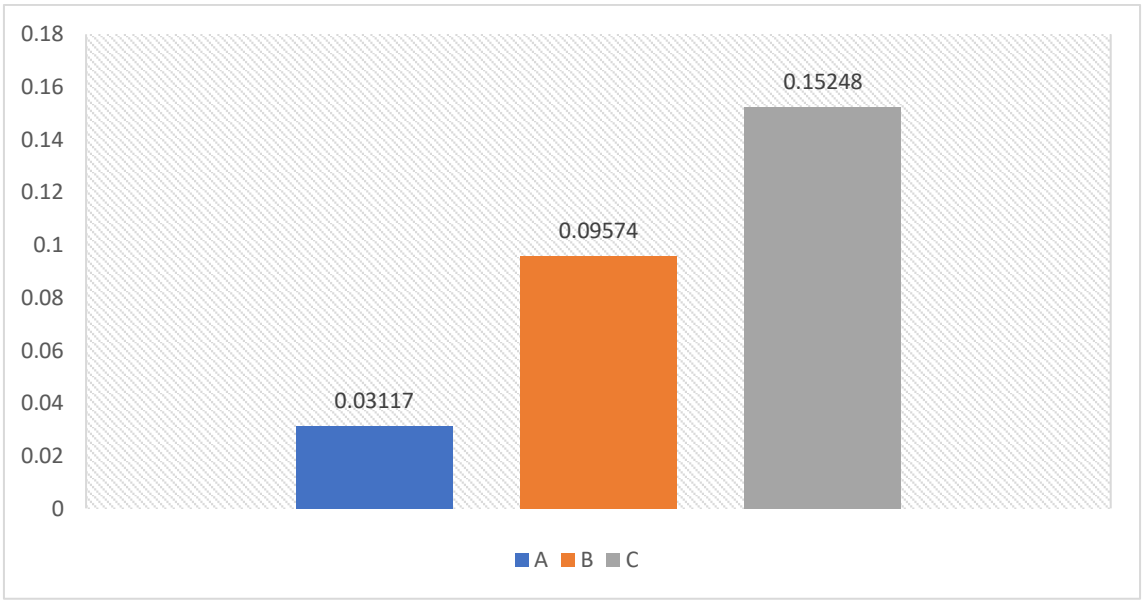

Fig. 20 Cd values across samples

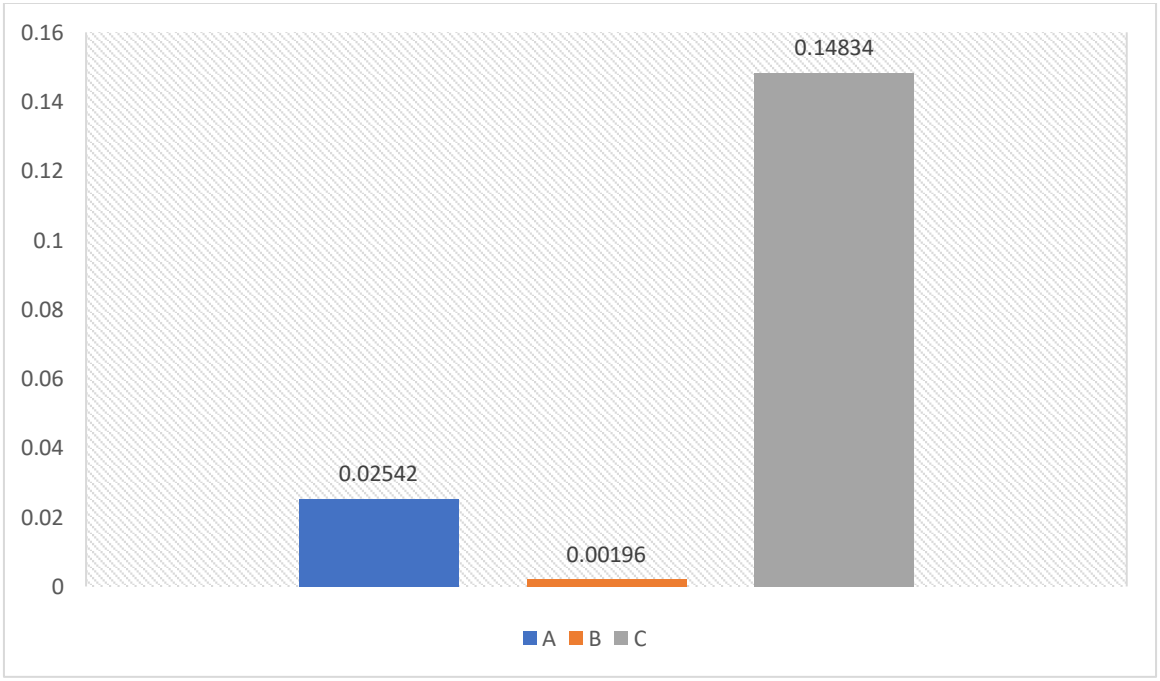

Fig. 21 Hg values across samples

Lead (Pb) was detected at 8.88 mg/L in Sample C, far exceeding the safe discharge limit of 0.05 mg/L, while Samples A and B also surpassed this threshold (Fig. 11). Lead contamination can arise from corrosion of pipelines or leaching from oil-bearing formations. Chronic exposure to lead impairs aquatic reproduction and poses neurotoxic risks to humans. Similar lead concentrations were reported by Eyankware et al. in Ughelli oilfields, reinforcing the need for pretreatment before discharge [6].

Zinc (Zn) values (Fig. 12) were highest in Sample C (5.497 mg/L), well above the WHO threshold of 3.0 mg/L. High zinc content in produced water has been linked to scaling additives and corrosion inhibitors, which are often used in offshore and onshore production. Al-Salmi et al. documented comparable zinc levels in Oman's oilfields and recommended membrane distillation for effective removal [3].

Magnesium and calcium values (Figs. 13 and 14) were elevated but within tolerable levels. Sample C had the highest levels for both Mg (8.54 mg/L) and Ca (17.4 mg/L), indicating high water hardness. These parameters contribute to scaling and clogging in piping systems but are not immediately toxic. Razak et al. identified similar values in treated produced water from Malaysian terminals [18].

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Potassium (K) concentrations were exceedingly high in all samples, with values nearing 10 mg/L in Sample C (Fig. 15), far above the trace level permissible in drinking water. Elevated potassium affects osmoregulation in aquatic species and reduces water suitability for agriculture.

Aluminum (Al) levels ranged from 0.36 mg/L to 0.85 mg/L, with Sample C again registering the highest (Fig. 16). Excess aluminum in water bodies has been associated with gill damage in fish and neurological effects in humans. Sample C also recorded the highest sodium (Na) level (Fig. 18), which can significantly affect soil and water balance.

Toxic heavy metals such as barium (Ba), mercury (Hg), and cadmium (Cd) were present in all samples at levels exceeding zero-tolerance thresholds. Barium concentrations in Sample C were the highest (Fig. 19), while mercury and cadmium levels also peaked in the same sample (Figs. 20 and 21). These findings raise serious environmental concerns, as all three metals are bioaccumulative and carcinogenic. According to Thomas, produced water containing such metals must undergo advanced treatment such as ion exchange or chemical precipitation to meet safety standards [19].

The consistently high values of heavy metals across samples—particularly in Sample C—indicate that produced water from hydrocarbon terminals is a complex effluent requiring multi-stage treatment. The observed concentrations align with those reported in earlier studies by Eyankware et al. [6], Al-Ghouti et al. [2], and Dickhout et al. [5], confirming that heavy metal contamination is a persistent challenge in oil-producing regions.

Analysis of variance

To statistically evaluate whether the variations in water quality parameters were influenced by sample location or inherent parameter differences, a two-way Analysis of Variance (ANOVA) was performed. The results are summarized in Table I, which displays the sum of squares (SS), degrees of freedom (df), mean squares (MS), F-statistics, and corresponding p-values for both rows (parameters) and columns (locations).

Table I Analysis of variance on sample parameters

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	35038856	21	1668517	2.269552	0.011779	1.812817
Columns	1958985	2	979492.3	1.332326	0.274784	3.219942
Error	30877327	42	735174.4			
Total	67875168	65				

The ANOVA result for the row factor—representing different water quality parameters—yielded an F-value of 2.27 with a p-value of 0.011779. Since this p-value is less than the standard threshold of 0.05, it indicates that significant variation exists among the measured parameters across all samples. This suggests that the parameters such as turbidity, COD, TOG, and heavy metals differed substantially in their distribution, confirming the heterogeneity of pollutants in produced water.

In contrast, the ANOVA result for the column factor—representing sampling locations A, B, and C—produced an F-value of 1.33 with a p-value of 0.274784, which is greater than 0.05. This means there was no statistically significant difference in the overall quality of water between the sampling locations. Essentially, while each parameter varied in concentration, the spatial variation between samples collected from different hydrocarbon terminals was not significant. This finding may be due to the uniformity in production techniques, geological characteristics, or chemical additives used across the sites.

These results are consistent with previous studies. Eyankware et al. reported similar statistical outcomes for produced water from Ughelli, where spatial differences were minimal due to overlapping production methods [6]. Al-Ghouti et al. also observed that variations in produced water quality are often more related to operational parameters than to geographic separation when oilfields share similar reservoir conditions [2].

The implication of the ANOVA analysis is that treatment approaches designed for one terminal may be effectively applied to others within the same basin or region. Furthermore, the significant differences between

parameters suggest that treatment systems must be multi-faceted, targeting specific contaminants rather than relying on general filtration or neutralization techniques.

CONCLUSION

This study achieved its aim of characterizing produced water from hydrocarbon terminals in the Niger Delta region and provides the following conclusions based on the project's four stated objectives:

1. Characterization of the composition of produced water from hydrocarbon terminals: Produced water from all three terminals exhibited a complex mixture of contaminants. Physicochemical analysis showed high turbidity (up to 47.9 NTU), COD (up to 2397.4 mg/L), BOD_5 (up to 19.84 mg/L), and TOG (up to 7630.8 mg/L). These exceed permissible discharge limits set by NUPRC and WHO. While pH (7.84–8.67), EC (685–1024 µS/cm), TDS (375.1–579.7 mg/L), and salinity (3.74–10.68 mg/L) remained within limits, the high organic and suspended solids content indicates poor effluent quality without treatment.

2. Investigation of the potential health risks and environmental impacts of produced water discharge: The presence of heavy metals such as Pb (8.88 mg/L), Cd (0.152 mg/L), and Hg (0.148 mg/L) significantly exceeds safe thresholds. These toxic substances can bioaccumulate in aquatic ecosystems, impair reproduction in fish, and cause neurological and organ damage in humans. Turbidity and high TOG levels further threaten aquatic photosynthesis and oxygen balance. Therefore, the discharge of untreated produced water poses significant environmental and public health risks.

3. Comparison of measured concentrations with WHO and NUPRC standards: All samples exceeded permissible limits for key parameters: turbidity (>15 NTU vs. 5 NTU limit), COD (>1100 mg/L vs. 150 mg/L), BOD_5 (>8.14 mg/L vs. 10 mg/L), TOG (>120 mg/L vs. 40 mg/L), Pb (>8.88 mg/L vs. 0.05 mg/L), and other metals. These results confirm regulatory non-compliance and emphasize the urgency for improved water management.

4. Recommendations for managing and treating produced water: Given the severity of contamination, a multi-stage treatment approach is recommended, combining physical separation, chemical oxidation, and membrane filtration. Centralized treatment may be adopted across terminals since ANOVA analysis revealed no statistically significant differences between locations. Regular monitoring and enforcement of regulatory limits are essential to ensure sustainable operations.

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