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COAST
JOURNAL OF THE SCHOOL OF SCIENCE
Special Issue 1, September, 2025 ISSN: 2714-3716
Coast, J. Sch. Sci. 7 (2): 1243 - 1254

BIODEGRADATION OF TOTAL PETROLEUM HYDROCARBONS IN PRODUCED FORMATION WATER BY INDIGENOUS BACTERIAL ISOLATES FROM DELTA STATE, NIGERIA

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https://dx.doi.org/10.4314/coast.v7i2.3s

Abstract
Produced formation water (PFW) is subsurface water brought to the surface during oil and gas production, and its improper disposal poses environmental risks, including water contamination and harm to biological indicators. This study investigated the biodegradation potential of indigenous bacteria in PFW samples from five oil sites in Delta State, Nigeria. Physicochemical analysis revealed a pH of 7.63±0.06, electrical conductivity of 940.33±0.33 µS/cm, turbidity of 1.26±0.60 NTU, total dissolved solids of 4706.66±6.66 mg/L, and total petroleum hydrocarbon (TPH) content of 0.06±0.00 mg/L. Bacterial counts ranged from $1.86 \pm 1.20 \times 10^5$ to $2.37 \pm 2.02 \times 10^5$ CFU/mL in nutrient agar, and from $3.66 \pm 0.66 \times 10^4$ to $6.66 \pm 1.66 \times 10^4$ CFU/mL in mineral salt agar. Isolated bacteria included *Acinetobacter baumannii*, *Acetobacterium* sp., *Enterococcus faecalis*, *Bacillus arbutinivorans*, and *Pseudomonas stutzeri*. Among them, *P. stutzeri* showed the highest degradation efficiency, reducing TPH to 0.048 mg/L over five weeks, followed by *E. faecalis*, *Acetobacterium* sp., and *B. arbutinivorans* (each to 0.05 mg/L). The findings demonstrate that indigenous bacteria present in PFW possess notable hydrocarbon-degrading capabilities and could be harnessed for bioremediation applications.
Keywords: Biodegradation, physico-chemical, produce water, bacteria, hydrocarbon.

Introduction

The growth of the petroleum industries in Nigeria and the marketing of petroleum products have made oil pollution a serious environmental concern. Also, produced formation water and oil spill from industries, filling stations, loading and pumping stations, petroleum product depots, during transportation and at auto mechanic workshops all contribute to soil contamination, and since soil is the home of many biological activities, its pollution has great negative effect on the biological entity present.

Produced formation water is defined as the water that exists in subsurface formations and is brought to the surface during oil and gas production. Large volumes of water produced during oil and gas extraction are generated in drought prone locations that are also experiencing an increase in population (Gazali *et al.*, 2017). The environmental concerns associated with produced formation water are degradation of soils, ground water, surface water, and ecosystems they support (Abdul *et al.*, 2017). Due to the fact that produced formation water contains elevated levels of dissolved ions (salts), hydrocarbons, and trace elements, untreated produced formation water discharges may be harmful to the surrounding environment. The most common practices for produced formation water disposal include land application or discharge, subsurface injection, and offsite trucking (Katie *et al.*, 2011).

Biotreatability of produced formation water is the use of biological entities such as microorganisms in the treatment or degradation of formation water. The ability to degrade produced formation water is exhibited by a wide v*ariety* of bacterial genera (Al-Ghouti *et al.*, 2019). In oil fields, almost all produced water contains oil and suspended solids (Klemz *et al.,* 2021). The discharge of these toxic constituents and contaminants to the aquatic environment pose threat to aquatic life and agricultural resources by altering the natural state of the aquatic environment. Bakke *et al.* (2013) opined that discharge of the wastes to fresh water environment affects agricultural resources and causes massive destruction to the aquatic life. Worldwide research has proven that produced formation water effluents are associated with high level of biological oxygen demand (BOD) and chemical oxygen demand (COD) which are generated from compounds of fatty acids. Since environmental pollution with petroleum products such as crude oil and produced water has been recognized as one of the most serious current problems especially when associated with accidental spills on large-scale (Kardena *et al.*, 2017), it is pertinent to implement cost effective and appropriate management measures in order to reduce or eradication such pollutions. Therefore, the current study was designed to using indigenous bacterial isolates from produced water for its treatment, so that when it is discharged into the environment after treatment, there will be no pollution

Materials and Methods

Sample Collection

Produced formation water was collected from oil well sites in Otorogu, Delta State of Nigeria. Five (5) PFW samples were obtained from various sites at the oil well and designated as: OWS1= PFW sample from oil well site 1, OWS2= PFW sample from oil well site 2, OWS3= PFW sample from oil well site 3, OWS4= PFW sample from oil well site 4, OWS5= PFW sample from oil well site. Abiotic control test tubes were prepared in the study which remained uninoculated and were used as baseline for comparison.

Bacteriological Analysis of Produced Formation Water

The quantification of total heterotrophic bacterial counts within the produced formation water was conducted according to by Pelczar *et al.* (1988). The resulting colony counts were used to calculate the total heterotrophic bacterial counts in the produced formation water samples, allowing for a quantitative assessment of the bacterial load present in the analyzed samples.

Isolation and Identification of Produced Formation Water Utilizing Bacteria

Produced formation water utilizing bacteria was enumerated by plating out 0.1mL of PFW on modified mineral salt medium. Mineral salt medium is composed of distilled water (1000 mL), K_2HPO_4 (1.73g), KH_2PO_4 (0.68g), $MgSO_4.7H_2O$ (0.1g), $FeSO_4.7H_2O$ (0.03g), NH_4NO_3 (1g), $CaCl_2.2H_2O$ (0.02g) (Mills *et al.*, 1978), to which 1% of PFW sample was added, using the spread plate technique. Enumeration was done after incubation of plates for 7days using the protocols of Holt *et al.* (1994).

Screening Test for PFW Utilizing Bacteria

The assessment of the purified bacterial isolates' capability to utilize Produced Formation Water (PFW) as their exclusive carbon and energy source was performed by adapting the methodologies of Okpokwasili and Okorie (1988) and Coleman *et al.* (2002).

Biodegradation of Components of Produced Formation Water using Shake Flask Method

The bacterial isolate with the highest optical density, indicating its potential for utilizing components of Produced Formation Water (PFW), was chosen for the biodegradation study. Biodegradation study was done using shake flask culture according to (Okpokwasili and Okorie, 1988).

Results

The physicochemical analysis of produced formation water as present in Table 1, revealed a pH, electrical conductivity, turbidity, total dissolved solid, chloride, nitrate, dissolved oxygen and biological oxygen demand concentration to be 7.63±0.06, 940.33±0.33 μS/cm, 1.26±0.60 NTU, 4706.66± 6.66 mg/L, 443.16±0.05 mg/L, 0.74±0.00 mg/L, 3.24±0.01mg/L and 0.73±0.02 mg/L respectively. Some heavy metals were also reported to be in produced formation water in different concentrations and they included zinc, chromium, cadmium, nickel and lead with concentrations of 0.33±0.00 mg/L, 0.07±0.00 mg/L, 0.04±0.00 mg/L, 0.03±0.01 mg/L and 0.06±0.00 mg/L respectively. The concentration of total petroleum hydrocarbons was found to be 0.06±.0.00 mg/L in produced formation water.

Total Bacterial counts in produced formation water are shown in Table 2. Results of the total bacterial counts ranged from 1.86±1.20 $\times10^5$ CFU/mL to 2.36±2.02$\times10^5$ CFU/mL on nutrient agar while on mineral salt medium, counts ranged 0.36±0.66 $\times10^3$ CFU/mL to 6.60±1.66$\times10^3$ CFU/mL. Highest and lowest total bacterial count of PFW on nutrient agar was obtained in samples OWS2. There was no significant difference in bacterial counts in the different samples in both nutrient agar and mineral salt agar.

Result of bacteria isolated from PFW is presented in Table 3. The bacterial isolates recovered from produced formation water were *Acinetobacter baumannii, Acetobacterium* sp., *Enterococcus faecalis, Bacillus arbutinivorans* and *Pseudomonas stutzeri.* All bacterial isolates were identified molecularly and all had percentage similarity of above 98 %.

The result of bacterial count during biodegradation of produced formation water for a period of six weeks is as shown in figure 1. For *Acetobacterium* sp., bacterial growth increased from 10.66±2.33x10^5 CFU/mL at week 0 to 124.00±1.00x10^5 CFU/mL at week 5. Bacterial counts of *P. stutzeri* ranged from 15.00±2.88 to 185.00±0.57$\times10^5$ CFU/mL. Bacterial counts of *B arbutinivorans* ranged from 8.00±0.57$\times10^5$ CFU/mL in week 0 to 123.66±0.88$\times10^5$ CFU/mL in week five while for *E. faecalis,* bacterial counts ranged from 10.33±0.33 to 126.00±0.05$\times10^5$ CFU/mL. In the control group, bacterial counts were very scanty and ranged from 0.80±1.0 to 10.63±0.33$\times10^5$ CFU/mL. In all bacterial group, highest count was observed at the fifth week with *Pseudomonas stutzer*i having the highest count. There were significant differences in bacterial counts during biodegradation with *p*-value less than 0.05.

The analysis of changes in physicochemical parameters over the biodegradation study is detailed in Tables 5a to 5b, with distinct variations noted across experimental groups compared to controls.

In Week 0, initial measurements indicated minor variations in parameters. The pH ranged from 7.63 in the *E. faecalis* group to 7.74 in the *P. stutzeri* group (Table 5a). Total Petroleum Hydrocarbon (TPH) concentrations varied slightly, with values ranging from 0.063 mg/L in the *P. stutzeri* setup to 0.66 mg/L in the *B. arbutinivorans* group (Table 5b).

By Week 1, significant changes were observed between the experimental and control groups. The control group's pH remained at 7.70, whereas the *P. stutzeri* group showed a decrease to 7.20 (Table 4.6a). In TPH measurements, the control group recorded 0.065 mg/L, compared to 0.061 mg/L in the *P. stutzeri* group (Table 5b). Over the six-week biodegradation period, TPH concentrations decreased across experimental setups, with the most substantial reductions observed in *P. stutzeri* and *E. faecalis*. The *P. stutzeri* group achieved the lowest TPH level at 0.04 mg/L, followed by *E. faecalis* at 0.05 mg/L, while *Acetobacterium sp.* and *B. arbutinivorans* reached 0.05 mg/L. In contrast, the control group's TPH concentration was 0.06 mg/L at the end of six weeks (Table 5b). 8.70 mg/kg respectively in seepage soil.

Table 1: Physicochemical parameters of produced formation water

Parameters	Concentrations
pH	7.63±0.06
EC (µS/cm)	940.33±0.33
Turbidity (NTU)	1.26±0.60
TSS (mg/L)	3.16±0.56
TDS (mg/L)	4706.66± 6.66
COD (mg/L)	15.26±0.34
HCO_3 (mg/L)	856.66±0.33
TPH (mg/L)	0.06±.0.00
DO (mg/L)	3.24±0.01
BOD (mg/L)	0.73±0.02

Table 2: Total bacterial counts in produced formation water (PFW)

	Media	
	THBC	PFWUB
Site	($\times 10^5$CFU/mL)	($\times 10^3$CFU/mL)
OWS1	2.23±1.76	6.66±1.66
OWS2	2.36±2.02	0.60±1.52
OWS3	1.86±1.20	0.40±1.00
OWS4	1.93±2.18	0.50±1.15
OWS5	2.20±3.05	0.36±0.66
p-value	0.45	0.43

Key: OWS1= PFW sample from oil well site 1, OWS2= PFW sample from oil well site 2, OWS3= PFW sample from oil well site 3, OWS4= PFW sample from oil well site 4, OWS5= PFW sample from oil well site 5, NA = Nutrient agar, MSM = Mineral Salt medium

Table 3: Bacterial isolates from produced formation water using mineral salt medium

Isolates Codes	Identity (%)	Bacterial isolates	Accession
B1	99.84	*Acinetobacter baumannii*	OR282470
B2	99.51	*Acetobacterium* sp.	OR282471
B3	99.68	*Enterococcus faecalis* YZ66	OR282472
B4	99.82	*Bacillus arbutinivorans* MGB4011	OR282473
B5	98.50	*Pseudomonas stutzeri* ATCC	OR282474

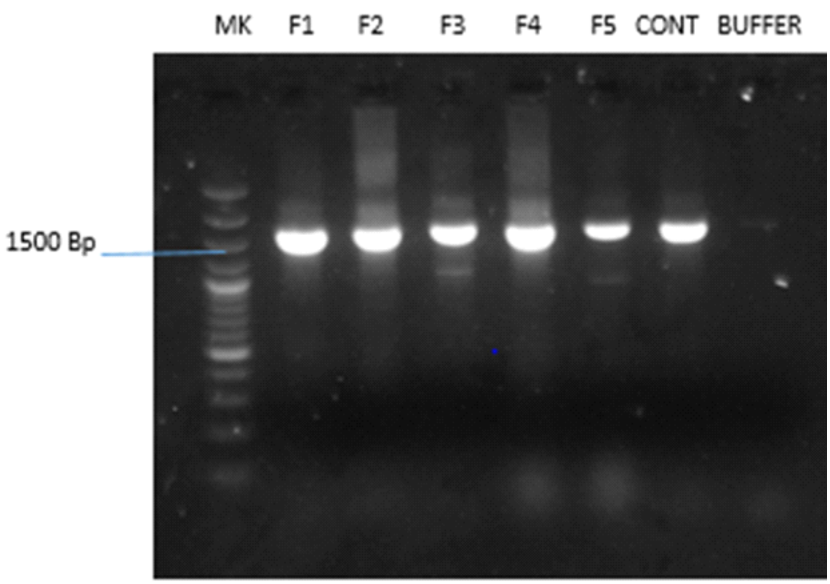

Plate 1: PCR product of 16SrRNA on 1% Agarose Gel

Table 4: Optical density (540nm) of bacterial isolates for biodegradation potential

Bacterial Isolates	Optical density
Acetobacterium sp.	0.27 ± 0.00^{c}
Pseudomonas stutzeri	0.33 ± 0.00^{f}
Bacillus arbutinivorans	0.32 ± 0.00^{e}
Enterococcus faecalis	0.28 ± 0.00^{d}
Acinetobacter baumanni	0.19 ± 0.00^{b}
Control	0.14 ± 0.00^{a}
p-value	0

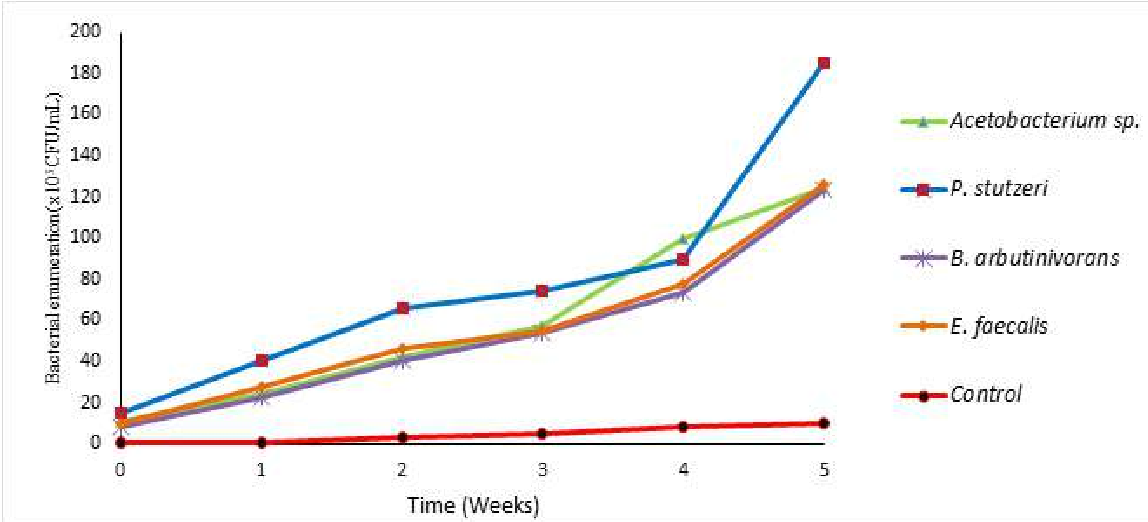

Figure 1: Bacterial enumeration (x10^5) during biodegradation of produced formation water by indigenous bacterial isolates

Table 5a: pH changes of produced formation water during biodegradation studies

	Bacteria					
Weeks	*Acetobacterium* sp.	*P. stutzeri*	*B. arbutinivorans*	*E. faecalis*	Control	p-value
0	7.63±0.06	7.74±0.02	7.70±0.00	7.63±0.07	7.66±0.03	0.45
1	7.43±0.03^{bc}	7.20±0.15^{ab}	7.66±0.03^{cd}	7.16±0.06^{a}	7.70±0.00^{d}	0
2	7.20±0.20^{b}	7.00±0.05^{ab}	7.46±0.03^{c}	6.86±0.15^{a}	7.60±0.10^{c}	0
3	6.96±0.05^{bc}	6.90±0.10^{b}	7.23±0.08^{c}	6.53±0.14^{a}	7.70±0.56^{d}	0
4	6.80±0.05^{b}	6.73±0.03^{b}	6.93±0.06^{b}	6.33±0.14^{a}	7.63±0.08^{c}	0
5	6.33±0.21^{ab}	6.56±0.17^{b}	6.57±0.12^{b}	6.03±0.03^{a}	7.63±0.11^{c}	0

50.05±0.00^{ab}0.04±0.00^{a}0.05±0.00^{ab}0.05±0.00^{a}0.06±0.00^{b}0.02**Key:** p values <0.05 = significant difference, p values >0.05 = no significant difference, Duncan multiple range (DMR) test: superscript along a row with similar superscript = not significant difference, superscript along a row with different superscript = significant difference

Table 5b: Changes in Total Petroleum Hydrocarbon (TPH) content (mg/L) of produced formation water during biodegradation studies

	Bacteria (mg/ L)					
eeks	*Acetobacterium* sp.	*P. stutzeri*	*B. arbutinivorans*	*E. faecalis*	Control	p-value
	0.06±0.00	0.06±0.001	0.06±0.00	0.06±0.00	0.06±0.00	0.05
	0.06±0.00^{a}	0.06±0.00^{a}	0.06±0.00^{a}	0.06±0.00^{a}	0.06±0.00^{b}	0
	0.0 6±0.00^{b}	0.0 5±0.00^{a}	0.06±0.01^{a}	0.05±0.00^{b}	0.06±0.01^{b}	0
	0.05±0.00^{c}	0.05±0.00^{a}	0.05±0.00^{c}	0.05±0.00^{b}	0.05±0.00^{d}	0
	0.05±0.00^{bc}	0.04±0.00^{a}	0.05±0.00^{c}	0.05±0.00^{b}	0.05±0.00^{d}	0
	0.05±0.00^{ab}	0.04±0.00^{a}	0.05±0.00^{ab}	0.05±0.00^{a}	0.06±0.00^{b}	0.0 2

50.05±0.00^{ab}0.04±0.00^{a}0.05±0.00^{ab}0.05±0.00^{a}0.06±0.00^{b}0.02**Key:** p values <0.05 = significant difference, p values >0.05 = no significant difference, Duncan multiple range (DMR) test: superscript along a row with similar superscript = not significant difference, superscript along a row with different superscript = significant difference

Discussion

The physicochemical parameters of the produced formation water samples were compared with the EGASPIN (Environmental Guidelines and Standards for Petroleum Industries in Nigeria) standard. EGASPIN is an arm of DPR (Department of Petroleum Resources) (EGASPIN, 2000). The pH of the produced formation water sample was 7.63±0.06 which is within EGASPIN pH limit of 6.5-8.5. The pH value observed was neither acidic nor alkaline. This is attributable to the presence of natural buffers in the produced formation water, which neutralize excess acidity or alkalinity through ionic equilibrium reactions (Felföldi *et al.*, 2010). The pH was also within the pH limit of 5.6 to 6.6 reported by Chikwe and Okwa (2016). Produced formation water pH is important because it affects other pollutants, in that, when it is very acidic, metals such as zinc, aluminum and copper are released causing them to accumulate in the food chain. Likewise, when it is more basic it causes the accumulation of the unionized ammonia ions (NH_3) which are known to be very toxic to plants and animals (Felföldi *et al.*, 2010). Long-term exposure to pH beyond the permissible limit affects the mucous membrane of cells (Josiah *et al.*, 2014).

The result of electric conductivity of the produced formation water samples showed that it was within the permissible limit as recommended by EGASPIN (1000 µS/cm). Electrical conductivity is a useful indicator of mineralization and salinity or total salt in water sample. Electrical conductivity is directly related to the concentration of ions in water and the higher the concentration of ions, the higher the conductivity. These conductive ions come from dissolved salts and inorganic materials (Oladipo and Adeboye, 2015). In this study the high electrical conductivity levels recorded are due to the elevated concentration of conducting ions originating from dissolved salts and inorganic constituents in hydrocarbon formations under high temperature and low pH conditions (Gambo *et al.*, 2015).

The turbidity is one of the important physical parameters for produced formation water, defining the presence of suspended solids in the water and causes the muddy or turbid appearance in produced formation water (Dauda *et al.*, 2016). The present study showed that the turbidity of the produced formation water was within the limits prescribed by EGASPIN standards (1–5 NTU). The turbidity values reflect the presence of inorganic particulate matter and non-soluble metal oxides, which contribute to the cloudy appearance of produced formation water.

Total suspended solid is the turbidity caused due to silt and organic matter. In the study area, the total suspended solid concentrations in the produced formation water were within EGASPIN recommended limit (<10mg/L). One component of water quality, total suspended solids (TSS), is both a significant part of physical and aesthetic degradation. The observed TSS reflects the presence of other pollutants, particularly nutrients and metals that are adsorbed onto suspended sediment particles. The presence of total suspended solids (TSS) confirms the inclusion of silt, decaying organic matter, industrial particles, and sewage-borne materials, which adsorb and carry nutrients and metals in suspension. High concentrations of suspended solids can cause many problems for stream health and aquatic life.

Total dissolved solids indicate the salinity behavior of the produced formation water. In the study, total dissolved solids value was 4706.66± 6.66 mg/L which was above EGASPIN standard permissible limit (500 mg/L). The high level of TDS reflects the significant concentration of soluble solids in PFW, necessitating appropriate treatment before discharge into receiving water bodies or reuse. Discharge of such high TDS water without treatment causes undesirable taste and gastrointestinal irritation (Suthar, 2011).

Chemical oxygen demand (COD) is an important parameter for characterizing produced formation water (Atuanya *et al.*, 2018). It is an evaluation used to measure the level of water contamination by organic matter (Sulaiman *et al.*, 2016). The COD value is usually higher than the biological oxygen demand (BOD) because some organic materials in the water that are resistant to microbial oxidation and hence not involved in BOD, could be easily chemically oxidized. The COD values obtained in this study is higher than that obtained by Ibrahim *et al.* (2021) who recorded a lower value of COD in produced formation water. High levels of BOD and COD are indicative of organic contaminants in the sampled PFW. High BOD level will increase the oxygen consuming ability of biodegraders in the receiving water body and thus renders the environment oxygen deficient. This will negatively affect living forms in the environment, thereby affecting environmental sustainability. this is why it is important to appropriately treat PFW before disposal.

The results of the bacterial properties of produced formation water revealed that produced formation water harbour specific indigenous microorganisms (Sun *et al.*, 2014). Bacterial counts were very high and agrees with earlier study by Chuma (2010) who reported bacterial count ranging from 4.50 - 14 × 10^5 CFU/mL. According to Turkayeva *et al.* (2017), population densities of microorganisms in produced formation water is usually not very high, but can reach up to 10^5 - 10^6 CFU/mL, suggesting that oil field waters constitute a nutrient-limited environment. The presence of high bacterial load in PFW demonstrates the abundance of macro- and micro-nutrients that sustain microbial growth and proliferation.

The bacterial species isolated from the produced formation water samples were *Acetobacterium* sp., *Pseudomonas stutzeri*, *Bacillus arbutinivorans* and *Enterococcus faecalis*. This is similar to the study of Mahdi *et al.* (2017) who isolated *Bacillus cereus*, *Acetobacterium* sp., *Pseudomonas stutzeri*, *Micrococcus* sp., *Staphylococcus aureus*, *Bacillus subtilis* and *Enterococcus faecalis* from produced formation water. Produced formation water contains many constituents such as heavy metals that are toxic to many microorganisms. Isolation of these bacteria confirms that these species withstand the harsh chemical and physical conditions of PFW and utilize hydrocarbons and other organic compounds present in PFW as their sole carbon and energy sources, through enzymatic oxidation and assimilation processes (Das & Chandran, 2011). Daehyun *et al.* (2018) reported that produced formation water contains bacterial populations including *Bacillus* species, *Enterococcus faecalis* and *Pseudomonas* species.

However, the results of this study were contrary to the results obtained by Sun *et al.* (2014) who detected *Rhodobacter*, *Trichococcus*, *Micrococcus*, *Enterococcus*, and *Bavariicoccus* strains in microtherm oil-production water from the Karamay Oilfield, Xinjiang, China. The results obtained in this study was found to be similar to the report by Kardena *et al.* (2017) who reported that *Pseudomonas* sp., *Enterococcus* sp. and *Bacillus* sp. were isolated from Oilfield-Produced formation water in Indonesia. The isolation and identification of *Bacillus* and *Pseudomonas* species from produced formation water is also a common phenomenon as it has been reported by Lipus *et al.* (2018) as bacteria that are amongst the main microbial communities in Bakken region produced formation water.

The optical density of receiving soil samples measured at 540 nm revealed that *Pseudomonas stutzeri* had the highest optical density. This is consistent with the findings of Sebiomo *et al.* (2010) who reported that optical density increases with exposure to hydrocarbon or lubricating oil. The fact that the highest optical density value was observed in *Pseudomonas stutzeri* culture indicates its superior ability to metabolize hydrocarbons and withstand toxic heavy metals, supported by its enzymatic machinery for hydrocarbon catabolism.

Conclusion

The results of this study clearly demonstrate that microbial treatment is an effective approach for the biodegradation of pollutants present in produced formation water (PFW), particularly Total Petroleum Hydrocarbons (TPH). Among the bacterial isolates used, *Pseudomonas stutzeri* and *Enterococcus faecalis* exhibited the highest efficiency in reducing TPH levels, achieving concentrations as low as 0.048 mg/L and 0.050 mg/L respectively over a six-week period. This significant reduction is a direct result of microbial metabolism, which also correlated with a decrease in pH—an indicator of active microbial degradation. Furthermore, the increase in bacterial population, especially in *P. stutzeri*, revealed strong adaptation and growth in the hydrocarbon-rich environment, reinforcing its potential for bioaugmentation strategies. In contrast, the control group showed minimal changes in both bacterial population and TPH concentration, highlighting the insufficiency of natural attenuation without microbial intervention. Physicochemical analysis revealed that PFW initially contained high levels of dissolved solids, chloride, and trace heavy metals like zinc, chromium, cadmium, and lead, underscoring its potential environmental toxicity. However, the biodegradation process moderated these impacts, as seen in the improved quality of water parameters across the experimental groups.

Recommendations

1. Industries, especially in oil and gas sectors, should incorporate bioaugmentation techniques using indigenous hydrocarbon-degrading bacteria such as *P. stutzeri* and *E. faecalis* to treat produced formation water before discharge. This will enhance pollutant removal and reduce environmental impact.
2. Isolating and using native microbial species that have adapted to the local environment offers a cost-effective and sustainable method for bioremediation. These bacteria are not only effective but also pose minimal ecological risk.
3. Environmental regulatory agencies should support research and implementation of microbial bioremediation through policies, funding, and standardization of microbial treatment protocols for oil-contaminated effluents.
4. Stakeholders, including industry workers, policymakers, and local communities, should be educated on the environmental and health benefits of microbial bioremediation to promote its wider adoption and integration into sustainable environmental management strategies.

References

Abdul, R., Abdul, I., Hadi, A., Wan Rosli, W., Mohd, Z. and Issham, I. (2017).

Drilling fluid waste management in drilling for oil and gas wells. *Ital. Assoc. Chem. Eng.,* 56: 186-193.

Al Disi, Z., Jaoua, S. and Al-Thani, D. (2019). Biodegradation of petroleum hydrocarbons by thermophilic bacteria isolated from Qatar. *Environ. Sci. Pollut. Res.*, 26(2), 1320–1331.

Al-Ghouti M., Al-Kaabi M., Ashfaq, M. and Dan, D. (2019). Produced formation water characteristics, treatment and reuse: A review. *J. Water Process Eng.,* 28: 222-239.

Atuanya, E.I., Adeghe, O.M. and Iyahen, E. (2018). Effects of storage on borehole water quality stored in plastic containers for prolong periods. *J. Appl. Sci. Environ. Manage.,* 22(12): 1925-1930.

Bakke, T., Klungsoyr, J. and Sanni, S. (2013). Environmental impacts of produced formation water and drilling waste discharges from the Norwegian offshore petroleum industry. *Mar. Environ. Res.,* 92: 154-169.

Chikwe, T.N. and Okwa, F.A. (2016). Evaluation of the physico-chemical properties of produced formation water from oil producing well in the Niger Delta Area, Nigeria. *Appl. Sci. Environ. Manage.,* 20(4): 1113-1117.

Chuma, C. O. (2010). Microbiological impacts of produced formation water discharges in nearshore shallow marine waters near Chevron's Escravos tank farm, Nigeria. *Afr. J. Microbiol. Res.,* 4(13): 1400-1407.

Coleman, N.V., Mattes, T.E., Gossett, J.M. and Spain, J.C. (2002). Biodegradation of cis-dichloroethene as the sole carbon source by a beta-proteobacterium. *Appl. Environ. Microb.*, 68: 2726–2730.

Daehyun, D., Kim, C., O'Farrell, D. and Oscar, T., Montoya, L. and Gieg, M. (2018). Microbial community analyses of produced formation waters from high-temperature oil reservoirs reveal unexpected similarity between geographically distant oil reservoirs. *Microb. Biotechnol.,* 11(4): 788–796.

Dauda, D. R., Duro, D. U. and IJah, J. J. (2016). Physicochemical and microbiological qualities of the abattoir wastewater in part of Minna Niger State. *Adv. Life Sci. Technol.,* 51: 224 – 229.

EGASPIN (2022). *Environmental Guidelines and Standards for the Petroleum Industry in Nigeria.* Available online at: https://www.iea.org/policies/8676-environmental-guidelines -and-standards-for-the-petroleum-industry-in-nigeria-egaspin][Accessed 12th September, 2024]

Felföldi, T., Heéger, Z., Vargha, M. and Márialigeti, K. (2010). Detection of potentially pathogenic bacteria in the drinking water distribution system of a hospital in Hungary. *Clin. Microbiol. Infect.,*16: 89–92.

Gambo, J.B., James, Y. and Yakubu, M.B. (2015). Physicochemical and bacteriological analysis of well water at crescent road poly quarters, Kaduna. *Int. J. Eng. Sci.,* 4(11):11-17.

Gazali, A. K., Alkali, A. N., Mohammed, Y., Djauro, Y., Dahir, M. D. and Kodomi, M. (2017). Environmental impact of produced water and drilling waste discharges from the Niger Delta petroleum industry. *IOSR J. Eng.,* 7: 22–29.

Holt, J.G., Krieg, N.R., Sneath, P.H. and

Staley, J.T. (1994). *Bergey's manual of determinative bacteriology*. Baltimore, MD: Williams & Wilkins. 56p.

Ibrahim, M. A., Mezughi, K.M., Triki, N.M. and Altayeb, S.A. (2021). Physiochemical characteristics of produced formation water in oilfields and its environmental impacts. *Int. J. Sci. Dev. Res.,* 6(2):288-300.

Josiah, J. S., Nwangwu, C. O. S., Omage, K; Akpanyung, O. E. and Amaka. D. D. (2014). Physicochemical and microbiological properties of water samples used for domestic purposes in Okada Town, Edo State, Nigeria. *Int. J. Curr. Microbiol. Appl. Sci.,* 3(6): 886-894.

Katie, G., Katharine, D. and Steve, D. (2011). Oil and gas produced formation water management and beneficial use in the Western United States. *Sci. Technol. Program Rep.,* 15: 77-81.

Klemz, A. C., Weschenfelder, S. E., de Carvalho Neto, S. L., Pascoal Damas, M. S., Toledo Viviani, J. C., Mazur, L. P., Marinho, B. A., Pereira, L. dos S., da Silva, A., Borges Valle, J. A., de Souza, A. A. U. and Guelli U. de Souza, S. M. A. (2021). Oilfield produced water treatment by liquid-liquid extraction: A review. *J. Pet. Sci. Eng.,* 199: Article 108282.

Kumar, M., Ghosh, P., Karmakar, S. and Dey, R. (2020). Bioaugmentation for hydrocarbon bioremediation: Current advances and perspectives. *Chemosphere, 260*, 127529.

Lipus, D., Roy, D., Khan, E., Ross, D., Vikram, A., Gulliver, D., Hammack, R. and Bibby, K. (2018). Microbial communities in Bakken region produced formation water. *FEMS Microbiol. Lett.,* 365: 1-11

Mahdi, Z.M., Al-Mahdawi, M.M. and Sabtie, H.A. (2017). Study of some physicochemical and bacteriological properties for Produced formation water of the Vortisand unit. *Saudi J. Life Sci.,* 36(5): 131-139.

Mills, A.L., Breuil, C. and Colwell, R.R. (1978). Enumeration of petroleum degrading marine and estuarine microorganisms by the most probable number method. *Can. J. Microbiol.*, 24: 552-557

Obayori, O. S., Ogunmolu, F. E. and Ilori, M. O. (2021). Biodegradation of hydrocarbons in produced water by indigenous bacteria. *Bioresour. Technol. Rep.*, 15: 100743. https://doi.org/10.1016/j.biteb.2021.100743

Oladipo, I. C. and Adeboye, O.A. (2015). Physicochemical and bacteriological analysis of well water used for drinking and domestic purposes in Ogbomosho, Nigeria. *Int. J. Curr. Microbiol. Appl. Sci.,* 4(9):136-145.

Onwosi, C. O., Odibo, F. J. C. and Ezeogu, L. I. (2020). Microbial community dynamics and biodegradation of crude oil-contaminated soil: Implications for bioremediation. *Sci. Afr.*, 7, e00229. https://doi.org/10.1016/j.sciaf.2020.e00229

Pelczar, M.J., Chan, E.C.S. and Krieg, N.R. (1986). *Microbiology*, 5th Edition. McGraw Hill Book Company.

Qin, W., Zhang, X., Yang, Q. andYu, Y. (2021). Biodegradation of petroleum hydrocarbons by bioaugmentation with Pseudomonas strains. *Environ. Pollut.,* 276: 116707.

Ramos, J. L., González-Pérez, M. M. and van Dillewijn, P. (2020). Hydrocarbon degradation by *Pseudomonas* species.

Curr. Opin. Biotechnol., 64, 215–223.

Sebiomo, A., Bankole, S.A. and Awosanya, A.O. (2010). Determination of the ability of microorganisms isolated from mechanic soil to utilize lubricating oil as carbon source. *Afr. J. Microbiol. Res.,* 4(21): 2257-2264.

Sulaiman, A.A., Attalla, E. and Sherif, M.A. (2016). Water pollution: source and treatment. *Am. J. Environ. Eng.,* 6: 88–98.

Sun, J., Xu, L., Zhang, Z., Yan, L., Yue-Qin, T. and Wu, X. (2014). Diverse bacteria isolated from microtherm oil-production water. *Antonie Van Leeuwenhoek* 105(2):401-11.

Turkayeva, A., Jamalova, G., Mussina, U., Oshakbayev, M., Timma, L. Pubule, J. and Blumberga, D. (2017). Chemical and microbiological nature of produced formation water treatment biotechnology. *Energy Procedia* 113: 116-120.

Wang, W., Shao, Z. and Wang, Y. (2020). Degradation of hydrocarbons and bioremediation of marine oil pollution by bacteria from the deep sea. *Sci. Total Environ.*, 716, 137008.

Zhu, M., Zhang, Y., Zhang, B. and Wu, M. (2020). Characterization of microbial communities and physicochemical parameters during bioremediation of oil-polluted soil. *Chemosphere,* 241: 125013. *Resources*, 34: 10-23.