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Bioremediation of Oilfield Produced Water using Rotary Bio-Reactors Cultured Bacteria and Fungi: A Case Study of a Niger Delta Oilfield

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***Abstract*—Physicochemical analysis and quantification of oilfield produced waters generated at the studied location in Port Harcourt, Nigeria, reveal an array of oilfield effluents. The water samples studied were originally acidic until first neutralisation at the API Separator Station before being discharged to the Bioremediation unit. The concentrations of heavy metals in the samples were generally too low to detect. For example, Arsenic, Mercury, and Vanadium were not detected in the water. Hydrocarbon concentrations were low, except in the water samples collected after skimming from the API Separator Station in the fourth, seventh, and eighth weeks. This resulted in high Oil and Grease values of 65, 30, and 25 mg/l, respectively. The mean oil and grease value recorded after bioremediation was 2.28 mg/l. Total Dissolved Solids (TDS) in the water samples were low, correlating with their low ionic content. The conductivity values followed the same trend as the TDS values. Phenol, MEA, Sulphide, Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Ammonia and Cyanides were all converted or degraded by almost 100% through bioremediation.**

***Index Terms*—Oil Field, Produced water, Bioremediation, Heavy metals, Niger Delta**

I. INTRODUCTION

1.1 Background of the study

More recently, the problem of produced water or wastewater effluent from oilfield operations and their disposal has gained public recognition. In many parts of the world, especially in developing countries, environmental issues are similar. Wastewater refers to liquid that has water-mostly in a continuous phase or vice versa, discharged after use from residences, business premises, processing industries and institutions. In general, wastewater can be characterised by its bulk or organic content, physical characteristics, and specific contaminants (Vicente et al., 2024)

Olukanni D.O. et al. (2014) affirmed that wastewater from domestic and business premises is often referred to as sanitary water; there is also processed wastewater, produced water from oilfield activities, etc. Each wastewater stream has unique quality and characteristics, which suggest the type of treatment required. The two divisions of wastewater – Domestic and Industrial effluent have different make-ups and often require various treatment processes such as physical, chemical, thermal and biological processes. Still, the basic biological processes are preferred over the other three.

According to Matild and Samuel (2024), biological treatment (Bioremediation) processes are considered an economically feasible, operationally friendly, and, above all, environmentally most acceptable method for treating wastewater effluents from oilfield operations, particularly the most polluted waters. For example, hydrocarbon contamination in aquifers can often be treated by injecting microorganisms into the well, where they follow the contaminant plume and convert the contaminants into harmless substances.

1.2 Bioremediation process

Bioremediation has helped in cleaning up oil spills, pesticides, and other toxic materials. For example, accidents involving huge oil tankers regularly result in large spills that pollute coastlines and harm wildlife (Wemedo, 2016). Bacteria and other microorganisms can convert the toxic materials in crude oil to harmless products such as CO_2. Adding fertilisers containing nitrogen, phosphorus, and oxygen to polluted areas promotes the growth of bacteria already present in the environment and accelerates the cleanup process. (Sharma, 2021). The occurrence of hydrocarbon-utilising bacteria and fungi, with certain percentages of hydrocarbon-utilisers recorded in the uncontaminated soil samples, indicated that hydrocarbon-utilising microorganisms occurred naturally in the soil of the study area, especially in areas with oil exploration activity (Wemedo, 2016).

II. MATERIAL AND METHODS

2.1 Materials and methods

The following materials, tools, accessories and equipment were used for the bioremediation process to commence for the treatment of waste effluent from the oilfield. They are API Oil Separator, Bio-reactor or Rotary Bio Disk (RBD), Polluted Water Settling Pit, Coagulation Pit, Sedimentation Basin, Bio-DAF Basin, Oil Skimmer, Coagulation Basin, Bio-Sludge Measuring Tank, Bio-Sludge Condition Tank, Caustic Soda, Alum, Cat ion Polymer, Air, Mixing aid (Mixers), Pumping aid (pumps), Air Blowing Aid (Blowers), Dehydrator, Incinerator, Burner, Conveyor Belt and Ash Box.

2.2 Design basis

The design basis in Table 1 was tabulated to understand the parameters of the average daily bioremediation process in the wastewater treatment operations.

Table 1: Quantity of polluted water to be treated by bioremediation source from WWT Unit of a Niger Delta oilfield

Constituents of Produced Raw Water	Average Quantity (bbl/hr)	% Average Quantity (%)	Discharge Time (hr/day)
Process water from the API outlet	746.4*	23.4	24
Spent Caustic	10.67*	0.4	24
Sanitary Water	94.16*	2.9	24
Oily rainwater	477.72*	14.9	24
Ballast Water	1883.24*	58.6	24
Total Produced Raw Water	3212.19	100	24

Note: Figures marked with * are taken as the design basis

2.3 Methods of produced water treatment process

The produced water treatment methodology enumerated below is based on the Port Harcourt refinery treatment manual, 2008 edition:

1. The produced water treatment equipment consists of a water clarifying system and a sludge treatment system.
2. The produced water is a water mixture from the process plant, crude tank farm, oily rain water, Ballast water, dimethylsulfoxide effluent, caustic spent water and sanitary water. The water is collected and settled in a large open pit (called the polluted water settling pit).
3. Through the coagulation basin and Bio-DAF basin, polluted water collected from the settling pit is sent to the API separator, where the upper-layer oil content is skimmed off using an oil skimmer. These basins are not used for normal operation; under emergency conditions, when the oil content exceeds 10 mg/lit, the bio-DAF system is activated.
4. In the coagulation basin, caustic soda, alum, and cation polymer are injected and mixed in a mixer. Before entering the bio-DAF basin, air-dissolved water pressurised by the bio-recycle pump is injected for air flotation. Air is then pressurised in the bio-pressure drum. An instrument-level controller automatically controls the water level in the bio-pressure drum.
5. Before entering the polluted water pit, the caustic spent water is first neutralised in the neutralisation pit. The produced water, sanitary water, and caustic spent water are mixed by aeration and then equalised using a blower.

6. The equalised produced water is pumped up to the rotary Bio-Disks (RBD) where bacteria and fungi are biologically cultured to eat up these pollutants. The Rotary Bio-Disk (RBD) rotates continuously to initiate contact between the bacteria/fungi and the produced water. The produced water feed pump is automatically operated before entering the bioreactor (RBD). The measuring tank measures water quantity.
7. At the inlet of a trough, the system (bioremediation) is then enhanced through constant injection of nutrients. Alum is also injected to promote the settling speed of fine bio-sludge in the sedimentation basin, in case of carry-over of suspended solids from the sedimentation basin. The treated water from the bioreactor (RDB) is gravity-fed to the sedimentation basin.
8. The treated water in the sedimentation basin is stored in the observation pit. The withdrawal of excess sludge (biosludge) from the sedimentation basin is fed to the sludge storage basin. The suspended solids of overflow water from the observation pit are less than 5 mg/lit as settleable suspended solids (SSS).

2.4 Bioremediation reactor section

Another technical term for the bioremediation reactor is the Rotary Bio-Disk (RBD). The RBD treatment method is based on natural biological processes. It consists of a 12-Cell Array with six segments per row, which rotates at 4 R/min (0.07 R/S). The bio-cell media segments (disk) are always partially submerged in the produced water cells. Aerobic biomass, consisting of bacteria, protozoa, and other microorganisms, attaches to and grows on the cells of the bio-reactor media surfaces.

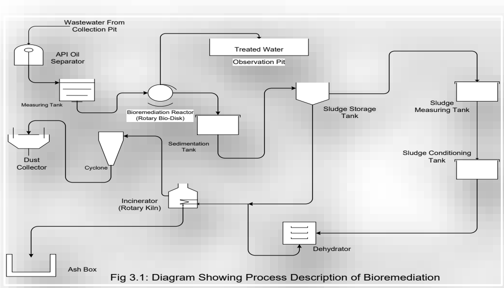

Figure 1: Process description of Niger Delta produced water bioremediation

1. Continuous supply of produced water and oxygen from the atmosphere assists the biomass in removing pollutants in the polluted water. Excess biomass growth is removed from the media by a rotating force. The residue is removed by following a conventional sedimentation basin, while the treated water is let into a water observation pit for standard and specification analysis before disposal.
2. From the sedimentation basin, the withdrawn bio-sludge enters the sludge storage basin by gravity flow, while a telescopic valve adjusts the flow rate. In the sludge storage basin, the bio-sludge is mixed by a mixer, which operates at no load. Therefore, the mixer operated continuously.
3. From the bio-sludge storage basin, the bio-sludge is pumped to a dehydrator through the sludge measuring tank and the sludge conditioning tank. The pump operates automatically on the storage level H-for High and L-for Low. Before entering the dehydrator, the sludge quantity is measured by the sludge measuring tank.
4. At the inlet of the sludge conditioning tank, cationic polymer is injected automatically and mixed by a mixer in the sludge conditioning tank. In cases of poor coagulation, coagulants (alum), cationic polymers, and caustic soda are used to increase solid recovery. The sludge flows to the dehydrator by gravity, where it is dehydrated into a cake.
5. The bio-dewatered cake is fed to the cake hopper through the belt conveyor and then is constantly charged into the rotary kiln through the screw conveyor equipped at the bottom of the hopper. The sludge charged into the rotary kiln is dried and then incinerated near the burner as it travels to the burner side through the pickup and feed vanes. The ash produced by incineration flows from the inner cylinder to the outer cylinder, then cools and is discharged through the port. It is automatically discharged into the ash box.
6. The exhaust gas coming from the rotary kiln is deodorised in the deodorising furnace after removal of dust through the cyclone and is then discharged into the stack by the exhaust fan, which cools it with fresh air. This concludes the entire pollutants treatment process, as illustrated in Figure 3.1.

2.4 Location and problems in the study process

The oil field location for this study is the Port Harcourt Refining Company Limited, considering the physicochemical characteristics of the generated samples. Time, Security, and financial constraints hinder data collection for this study, as not enough time was allotted for proper data evaluation, given that natural bioremediation takes longer to complete. This also made it impossible for the researcher to extend the study to other oilfield locations in the Niger Delta, especially the Okrika axis, due to the crisis there.

However, enhanced bioremediation is another effective means of obtaining data. Therefore, enhanced bioremediation is the basis for this study, which Osioko *et al.* (2016) also carried out.

2.5 Quality control/quality assurance

The sole purpose of the treatment process is to determine how toxicity or toxic constituents in produced water are removed or consumed by bacteria through bioremediation, following Sharma (2021). These polluting constituents are:

I. pH
II. Biological Oxygen Demand (BOD)
III. Chemical Oxygen Demand (COD)
IV. Suspended Solids (SS)
V. Phenol
VI. Oil and Grease
VII. Total Cyanide (T-CN)
VIII. Mono Ethanol Amide (MEA)

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However, to determine whether these toxic constituents are removed or mitigated from the polluted water, laboratory analysis of the polluted water before and after the bioremediation treatment process (i.e., for both wastewater and treated water) is needed. These samples are physically and chemically analysed. These analyses are carried out in accordance with the recommended practices identified by the regulatory Authorities. Other parameters considered are:

I. Temperature
II. Pressure
III. Turbidity
IV. Appearance

2.6 Methods of data analysis

Data collected from the quality control laboratory analysis result sheets were used to carry out a comparative analysis between the results and the set limitation standards by the regulatory Authorities, as exemplified by Johnson, S. J, (2003. The collected data were based on eight (8) weekly laboratory analyses of the collected effluent.

The sample point for:

I. Raw water (RWBD) is the rotary Bio-Disk (Bio-Reactor) entry point
II. Treated water (TWBD) is the Observation Pit entry point.

2.7 Data gathering method

Data gathering for the study was carried out based on eight (8) consecutive operational weeks of laboratory analysis and standards set by the regulatory Authorities. This is the usual practice of many researchers in bioremediation experiments, so we worked based on the data-gathering formats of Johnson, S. J. (2003).

2.8 Effluent analysis method

The values of each parameter were determined by the following methods, illustrated in Table 3.2.

Table 2: Parameters and their methods of determination

	Parameter	Method used
	Temperature	Thermometer.
ii.	Pressure	Barometer
iii.	PH	PH meter
iv.	Oil and Grease	Spectrophotometer
v.	Mono Ethanol Amide (MEA).	Solvent Extraction
vi.	Turbidity	Absolute turbidity method with the aid of an integrated sphere instrument.
vii.	Total Cyanide	Atomic Adsorption Spectroscopy
viii.	Phenol	Solvent Extraction and CG-MS
ix.	Biological Oxygen Demand	BOD Bottle Test

x.	Chemical Oxygen Demand	COD Test
xi.	Suspended Solids	Filtration Test

2.9 Analytical model applied in the study

The model applied is a Stochastic (Probabilistic) model that is statistically based, incorporating the randomness of the physical and chemical processes being studied with decision-making under conditions of risk. A hypothesis is tested through observed evidence in order to determine the probability that it is upheld by fact. The test concerns the relationship between the variables. If the tested relationship fails to yield conforming results, the hypothesis would be rejected. It is usual for statistical testing and interpretation to start by testing the null hypothesis of no difference. In contrast, the alternative hypothesis is positive, i.e., there is a difference, as attested by Akinsemolu, A., & Onyeaka, H. (2025).

According to Agibayeva et al. The analytical model is based on test classification of physicochemical characteristics of the critical parameters of the studied location, hence:

Ho: $\mu_0 = 0$ There is no difference between the specifications of the regulatory bodies and the data generated, i.e. the oil and gas operation does not impose a negative impact on the environment.

Ha: $\mu_0 \neq 0$: There is a difference between the specifications of the regulatory bodies and the data generated, i.e. the oil and gas operations are imposing a negative impact on the environment

$t_{cal} = \frac{d-\mu_o}{sd}$ ------(1)

where $\mu_o = 0$

That I; $\frac{Mean-0}{std\ error\ of\ difference}$

Where;

d = mean difference

μ_o *= population mean difference*

0 = Zero

d = std error of the difference $But: sd = \frac{standard\ Deviation}{\sqrt{n}}$ ------(2)

III. RESULT AND DISCUSSION

This chapter presents data from samples collected before and after bioremediation (as RWBD). It illustrates an eight-week consecutive data collection process, using direct observation of the processes and limitations (Design Specs Values) standards set by the Regulatory Agencies, as ascertained by Swannell, R. J., et al., 1996. The results, presentations, analysis of data collected, findings and discussions are given below;

3.1 Weekly result analysis for bioremediation of oilfield raw water against treated water

The collected data were based on eight (8) weekly laboratory analyses of the effluent, conducted every Wednesday at 0600 hours, and the findings are tabulated below in bi-weekly format.

The sample point for:

I. Raw water (RWBD) is the rotary Bio-Disk (Bio-Reactor) entry point
II. Treated water (TWBD) is the Observation Pit entry point.

Table 3: Week one to week two results

Parameter	Week 1		Week 2	
	RWBD	TWBD	RWBD	TWBD
pH	8.24	7.08	7.58	6.88
BOD, mg/l	1260	10.24	1280	14.14
COD, mg/l	920	78	700	88
OIL/GREASE, mg/l	15	<0.05	15.5	1.40
TOTAL CN, mg/l	20.83	0.44	23.7	0.85
AMMONIA, mg/l	2.40	0.01	2.46	0.01
PHOSPHATE, mg/l	7.45	0.02	0.78	0.02
PHENOL, mg/l	558	0.07	630	<0.01
SULPHIDE, mg/l	6.30	0.01	18.0	0.02
TSS, mg/l	54	2	67	4.0
MEA, mg/l	40	1.6	50	0.3
COND., ms	704	625	117	163
TEMP, ºC	24.7	25.1	24.7	25.1

Table 4: Week three to week four results

Parameter	Week 3		Week 4	
	RWBD	TWBD	RWBD	TWBD
pH	8.40	7.07	7.92	8.07
BOD, mg/l	1491	18.68	2194	13.25
COD, mg/l	790	110	900	122
OIL/GREASE, mg/l	12.0	2.0	15.00	5.00
TOTAL CN, mg/l	21.86	0.29	22.59	0.9
AMMONIA, mg/l	1.78	0.03	0.45	0.02
PHOSPHATE, mg/l	1.5	0.03	0.31	0.01
PHENOL, mg/l	431	<0.01	437	<0.01
SULPHIDE, mg/l	1.70	<0.01	8	0.03
TSS, mg/l	67	4	56	3.10
MEA, mg/l	184	1.1	60	1.3
COND., ms	516	354	371	340
TEMP, °C	24.7	25.1	24.7	25.1

Table 5: Week five to week six results

Parameter	Week 5		Week 6	
	RWBD	TWBD	RWBD	TWBD
pH	8.49	7.87	8.29	7.57
BOD, mg/l	1861	19.20	1450	19.56
COD, mg/l	436	88	2643	106
OIL/GREASE, mg/l	30	2.0	65.0	2.20
TOTAL CN, mg/l	26.54	0.45	32.67	0.92
AMMONIA, mg/l	2.01	0.04	3.61	<0.01
PHOSPHATE, mg/l	0.91	0.03	7.61	0.01
PHENOL, mg/l	230	<0.01	786	<0.01
SULPHIDE, mg/l	3.8	<0.01	4.76	<0.01
TSS, mg/l	76	4.20	68	1.2
MEA, mg/l	160	1.2	332	1.8
COND., ms	421	376	348	334
TEMP,	24.7	25.1	24.7	25.1

Table 6: Week seven to week eight results

Parameter	Week 7		Week 8	
	RWBD	TWBD	RWBD	TWBD
pH	7.66	7.26	8.14	7.53
BOD, mg/l	2502.8	10.48	1632	22.61
COD, mg/l	521	126	1500	78
OIL/GREASE, mg/l	15	4.60	25.0	1.00
TOTAL CN, mg/l	25.1	0.72	27	0.01
AMMONIA, mg/l	6.29	<0.01	11.17	0.01
PHOSPHATE, mg/l	8.31	0.04	9.15	0.02
PHENOL, mg/l	1202	<0.01	201	<0.01
SULPHIDE, mg/l	7.27	<0.01	8.01	<0.01
TSS, mg/l	24	1.9	24.00	4.04
MEA, mg/l	76.00	14.4	396.00	18.4
COND., ms	178.00	133	195	128.1
TEMP,	24.7	23.2	24.7	25.1

Table 7: Design quality specification for raw and treated water from bio-disk (Bioremediation reactor)

Parameter	Design basis	RWBD	TWBD
pH	6-8.5	7-8.5	6-8.5
BOD, mg/l	3250	3233	10-20
COD, mg/l	4250	4247	150
OIL/GREASE, mg/l	10-20	10-20	5
TOTAL CN, mg/l	1.0	28	1.0
NH_3, mg/l	0.6	3.2	0.05
PHOSPHATE, mg/l	0.4	7.9	0.05
PHENOL, mg/l	2.0	2000	0.05
SULPHIDE, mg/l	10	10	0.02

TSS, mg/l	30	50-100	5
MEA, mg/l	35	1560	25
COND. ms	300	125	306.7
TEMP, °C	15-35	15-35	15-35

Table 8: Summarised results of the experiment treated water bio-disk (TWBD)

Parameter	WE EK 1	WE EK 2	WE EK 3	WE EK 4	WE EK 5
pH	7.08	6.88	7.07	8.07	7.87
BOD, mg/l	10.2 4	14.1 4	18.6 8	13.2 5	19.2 0
COD, mg/l	78	88	110	122	88
OIL/GRE ASE, mg/l	<0.0 5	1.40	2.0	5.00	2.0
TOTAL CN, mg/l	0.44	0.85	0.29	0.9	0.45
AMMONI A, mg/l	3.86	3.90	2.20	0.26	0.14
PHOSPH ATE, mg/l	0.62	0.25	0.03	0.19	0.18
PHENOL, mg/l	0.07	<0.0 1	<0.0 1	<0.0 1	<0.0 1
SULPHID E, mg/l	0.01	0.02	<0.0 1	0.08	<0.0 1
TSS, mg/l	2	4.0	4	3.0	4.0
MEA,	1.6	0.3	1.1	1.3	1.2
COND. ms	625	163	354	340	376
TEMP, ^{O}C	25.1	25.1	25.1	25.1	25.1

Table 9: Summarised results of the experiment treated water from bio-disk (TWBD)

Parameter	Week 6	Week 7	Week 8	Mean Value
pH	7.57	7.26	7.53	7.42
BOD, mg/l	19.56	10.48	22.61	16.02
COD, mg/l	106	126	78	99.5
OIL/GREASE, mg/l	2.20	4.60	1.00	2.28
TOTAL CN, mg/l	0.92	0.72	0.01	0.57
AMMONIA, mg/l	<0.01	<0.01	0.09	0.018
PHOSPHATE, mg/l	0.38	0.28	0.18	0.022
PHENOL, mg/l	<0.01	<0.01	<0.01	0.018
SULPHIDE, mg/l	<0.01	<0.01	<0.01	0.014
TSS, mg/l	1.2	1.9	4.00	3.06
MEA,	1.8	14.4	18.4	5.01
COND. ms	334	133	128.1	306.7
TEMP, ^{O}C	25.1	23.2	25.1	24.9

Table 10: Mean treated water values for designed and generated specification bases showing the level of compliance

Parameter	Mean design	Generated mean value
pH	7.25	7.42
BOD, mg/l	15	16.02
COD, mg/l	150	99.5
OIL/GREASE, mg/l	5	2.28
TOTAL CN, mg/l	1.0	0.57
AMMONIA, mg/l	0.05	1.31
PHOSPHATE, mg/l	0.05	0.26
PHENOL, mg/l	0.05	0.018
SULPHIDE, mg/l	0.02	0.014
TSS, mg/l	5	3.06
MEA, mg/l	25	5.01
COND., mg/l	300	306.7
TEMP, ^{O}C	25	24.9

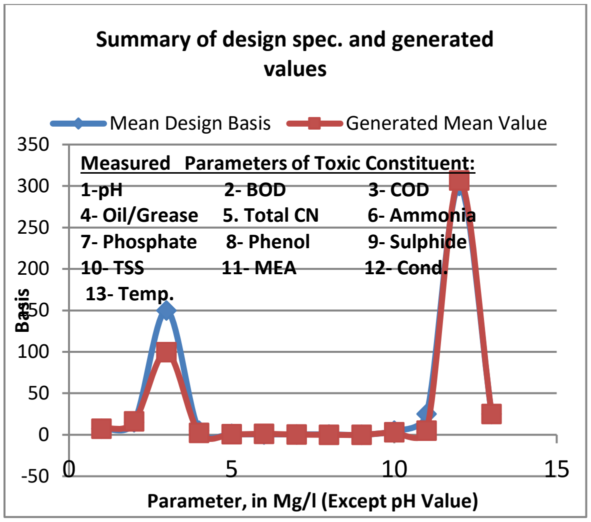

Figure 4: Level of compliance of the studied parameters against the design specification

3.2 Discussion of results

3.2.1 The pH Value

The average pH value for the eight weeks under review was near freshwater (7.08), after treatment to remove its sour state, which was 8.24 in week four. The mean pH over the eight weeks is slightly acidic (pH 7.24).

3.2.2 Biological Oxygen Demand (BOD)

The BOD result was also fairly accurate and appropriately degraded, given the highest value of 2502 mg/l in week seven to its lowest treatment value of 10.24 mg/l. The mean value of 16.2 mg/l was achieved over the entire period. This indicates that degradation was almost 100%.

3.2.3 Chemical Oxygen Demand (COD)

The COD result was fairly accurate, given the highest pre-treatment value of 2643 mg/l in week six of the review period. The lowest degraded rate of 78 mg/l was achieved in weeks 1 and 8. The acceptable value under the regulatory standard is 150 mg/l. The mean degraded value obtained is 99.5 mg/l.

3.2.4 Oil and Grease (O&G)

The regulatory standard for oil and grease content is 5 mg/l. The highest value of 165 mg/l from the sample was in week six (6), which was above the design treatment standard. However, the lowest post-treatment result was <0.05 mg/l. The mean standard value was 2.28 mg/l.

3.2.5 Total Cyanide Content (TCC)

The acceptable total cyanide content in the raw water sample is 1.0 mg/l, and the mean value obtained from the studies is 0.57 mg/l. Though the highest value of 32 mg/l was obtained in week six (6) before treatment, and the lowest value of <0.01 mg/l was obtained in week eight after treatment with bioremediation.

3.2.6 Ammonia, phosphate, sulphide and phenol contents

The acceptable design specifications for these constituents are 0.005 mg/l. The highest values of 11.17 mg/l for ammonia, 9.15 mg/l for phosphate, 18 mg/l for sulphide, and 1202 mg/l for phenol were analysed during pre-treatment sampling in week two (2), week eight (8), week two (2), and week seven (7), respectively. However, during post-treatment sampling, the values range from 0.02 mg/l to <0.01 mg/l, which are infinitesimally lower than the regulatory specification values.

3.2.6 Total Suspended Solids

The design basis for total suspended solids is 30.0 mg/l. At week five, the highest total suspended solids value of 76.0 mg/l was recorded during pre-treatment, with the lowest of 1.2 mg/l in week six. This signifies a successful reduction as compared to 5.0 mg/l. The mean value for the entire week under review is 3.16 mg/l.

3.2.7 Mono-Ethylene Amide (MEA)

The mean value obtained from the results is 5.01 mg/l, compared with the regulatory standard of 25.0 mg/l. For the pre-treatment sampling, the highest value obtained is 396 mg/l in week eight (8), while the lowest post-treatment value obtained is 0.3 mg/l. This is a successful degradation result as compared to 25.0 mg/l.

3.2.8 Conductivity

The acceptable conductivity values, as specified by regulatory agencies, are 300 ms for pre-treatment sampling and 125.7 mg/l for post-treatment sampling. The highest generated pre-treatment sampling value is 704 ms in week one (1), and the highest post-treatment sampling result of 621 ms was obtained in the first week. The mean conductivity value for the study period is 306.7ms.

3.2.9 Temperature

The temperature values are controlled and kept within the room temperature range of 25°C on average.

IV. CONCLUSION

All polluted water samples collected from the facilities were alkaline after initial neutralisation, but remained almost neutralised after bioremediation.

The produced water samples collected before neutralisation were also acidic. The acidity cannot be attributed to the effluent generated at these facilities (10). Oil and grease concentrations were generally low, except for the second week's samples. The degree of degradation of Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) was almost one hundred per cent (100%). The levels of inorganic and heavy metals, such as vanadium, Arsenic, Mercury, etc., were generally low, except for phosphate content. The high levels of oil and grease observed during sampling during the pre-bioremediation stage have been completely consumed or degraded at the post-bioremediation stage.

Total Cyanide, Ammonia, Sulphide, Mono-Ethylene Amide, and Total Suspended Solids were also low in the sample due to pretreatment and skimming at the API separator section before proper bioremediation could take place. The mean value of the accuracy of the conductivity signifies the accuracy of the entire result.

During this study exercise, it was discovered that factors other than normal laboratory shortcomings could affect the reliability of data obtained from the sample analysis.

These factors include:

i. Sampling techniques: The effects of sloppy techniques and poorly maintained equipment on the accuracy of results are obvious. There are, however, subtle issues that can affect accuracy despite the analyst's best efforts.

ii Some constituents like pH, BOD and COD must be analysed on site at the time of sampling or fixed so that the constituent concentration is not altered.

iii. Levels must be determined at the time of sampling. Sulphide can be determined on-site by analysis. An effort must be made to prevent precipitation.

iv. The high concentrations of COD, BOD, TSS and turbidity, and low Oxygen content of the collected sample were attributed to the overflow of the tank farm drainage systems.

v. Samples should be analysed as soon as possible to prevent degradation of the constituents. Time for analysis of constituents should be determined within 24 hours. Samples should not be exposed to extremes of heat or cold.

APPENDICES

Appendix A

Effluent Limitation for Oil and Gas Installations Guideline for Produced Oilfield Water (EGASPIN, 2015)

Pollutant or Effluent Characteristics		Compliance Limit		Maximum for any 30 consecutive days Period
S/N	Parameters	Inland Areas	Near Shore	Off Shore
1.	pH	6.5-8.5	6.5-8.5	No Limit
2.	Temperature, ^{o}C	35	40	-do-
3.	Oil and Grease, mg/l	10	20	48
4.	Salinity as Cl^{-}, mg/l	600	2000	No Limit
5.	Turbidity, mg/l	10	15	-
6.	TDS, mg/l	2000	5000	-do-
7.	TSS, mg/l	50	50	-do-
8.	COD, mg/l	40	No Limit	-
9.	BOD, mg/l	10	-do-	-
10.	Pb^{2+}, mg/l	0.05	-do-	-
11.	Total Iron, mg/l	1.0	-do-	-
12.	Copper, mg/l	1.5	-do-	-
13.	Zinc, mg/l	1.0	-do-	-

Appendix B

World health organisation specification for drinking water (WHO, 2021)

Quality parameter	Permissible limit
PH	6.0 - 8.5
Total Hardness mg/L	500.0
Turbidity NTU	5.0
Total Dissolved Solids	500.0
mg/L	>/ 3.0
Dissolve oxygen mg/L	0.20
Oil and Grease mg/L	0.001
Phenol	0.50
Ammonia	250.0
Chloride	400.0
Sulphate	10.0

Nitrate	0.5
Surfactant	0.01
Cadmium	0.05
Chromium	1.0
Copper	0.01
Cyanide	0.30
Iron	0.05
Lead	0.01
Selenium	200.0
Sodium	5.0
Zinc	0.05
Manganese	0.001
Mercury	0.05
Arsenic	

Appendix C

Abbreviations used in the study

API: American Petroleum Institute

EGASPIN: Environmental Guidelines and Standards for the Petroleum Industry in Nigeria

EPA: Environmental Protection Agency

BOD: Biological Oxygen Demand

C.F: Correction factor

CG-MS: Gas Chromatography- Mass Spectroscopy

CLARRC: Contaminated Land Assessment and Remediation Research Centre

COD: Chemical Oxygen Demand

DAF: Dissolved Air Flotation

DO: Dissolved Oxygen

NUPRC: Nigeria Upstream and Down Stream Regulatory Commission

FEPA: Federal Environmental Protection Agency

FME: Federal Ministry of Environment

MEA: Mono-Ethylene Amide

mg/l: Milligram per Litre

NESRDA: National Environmental Standard Regulatory Development Agency

pH: Hydrogen ion concentration

PPM: Part Per Million

RDB: Rotary Bio-Disk

RWBD: Raw Water from Bio-Disk

SS: Sums of Squares

TCN: Total Cyanide

TSS: Total Suspended Solids

TWBD: Treated Water from Bio-Disk

TDS: Total Dissolved Solids

TSS: Total Suspended Solids

WHO: World Health Organisation

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Conflict of interest

There are no conflicts associated with this research to declare

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