

Improved Management of Produced Water from Wells in Nigeria's Niger Delta

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Abstract—Management of produced water from Nigeria's Niger Delta wells was investigated, including a detoxification of the produced water using activated carbon adsorption system. The produced water was characterized based on the physicochemical properties of samples obtained from two different wells and relevant parameter values were experimentally determined. We found, for instance, that the range of pH, Total Dissolved Solids (TDS), Total Suspended Solids (TSS), Electric Conductivity (EC), bicarbonate (HCO₃) and Chloride (Cl⁻) values are 7.42 – 7.46, 12171.50 – 28016.80, 183.21 – 270.49, 35.10 – 39.50, 488.87 – 601.3, and 7149.07 – 18495.44, respectively. These results suggest that not all parameter values were within specification recommended by Nigeria's Department of Petroleum Resources (DPR), and thus require some level of treatment and management of the produced water in order to either reduce or eliminate the detrimental effects of produced water disposal or use. Results obtained after treating the produced water show that activated carbon adsorption can be used to treat and manage produced water by removing heavy metals, colour, odour, solids (mainly suspended solids), and oil. However, the activated carbon detoxification process was not effective in handling dissolved solids, salt ions, chloride and bicarbonates. Thus, it may be useful to combine the activated carbon adsorption process with other wastewater treatment techniques.

Keywords— Produced water management, activated carbon adsorption detoxification, produced water treatment, Niger Delta oil well.

I. INTRODUCTION

Oil and gas produced from reservoirs alongside large volumes of produced water is often considered a loss to operators and this has been responsible for operator's focus in developing new and improved methods for produced water management. The water found with oil and gas are usually located just below the hydrocarbon zone, though sometimes the water is found within same zone as the oil. Water cut in producing oilfields increases with reservoir depletion (Emam et al, 2014) and we expect larger volumes of this water to come from oil wells rather than from gas wells since oil wells are sometimes flooded with water with the objective to enhance oil recovery whereby the oil is forced to the production wells. The water produced after flooding, the so-called produced water (PW), can have varying compositional and characteristic behaviour which is usually controlled by the geological characteristics of each reservoir (Chinwe and Okwa, 2016). Produced water has a complex compositional characteristics which are a function of the several compounds that vary in concentration between wells and over the lifetime of a well (Udeagbara et al, 2021). Those which are of particular environmental concern include dispersed oil, aromatic hydrocarbons and alkylphenols (AP), heavy metals, and naturally occurring radioactive material (NORM) are of particular environmental concern (Neff et al, 2011).

Locally, there has been continued interest in Nigeria's Niger Delta on how best to manage produced water from Niger Delta wells that would result in better production efficiency and mitigated environmental impact that would support the United Nations – Sustainable Development Goals (UN-SDGs). Some questions still remain to be answered on better analysis of the physico-chemical composition of produced water from Niger Delta wells as well as establishing an environmentally friendly detoxification and discharge strategy. The two main objectives of this work are to compositionally characterize produced water

from Niger Delta formations as well as to determine an effective solution for the detoxification of the produced water using the process of activated carbon adsorption.

II. MATERIALS AND METHODS

In this work, produced water samples from two wells in the Niger Delta town of Nembe, Bayelsa State, were obtained, treated, analysed and characterized based on physio-chemical parameters. The analysis results were compared against stated standards to determine the levels of impurities present in the solution. The produced water was then passed through an adsorption plant to remove the impurities. The adsorption plant uses activated carbon as the adsorbent. However, the water sample passed through a sediment filter before the passing of the powdered activated carbon filter in the plant. After the adsorption process, the treated produced water was analysed and characterized based on its physio-chemical parameters and compared against stated standards in order to ascertain the effectiveness of the treatment process and to determine if the treated water can be used or discharged without harming the environment. Physicochemical parameters such as pH, total dissolved solids, electrical conductivity (EC), and some other metallic concentrations were determined.

A. Materials for Water Analysis

Different instruments and equipment were used to carry out several tests on the produced water samples to indicate the level of certain parameters that could be toxic to the environment. The instruments and equipment used during the water analysis include the following: multi-parameter photometer kit; drying oven; glass wares; filtration assembly with fibre glass filter papers; electric weighing balance; magnetic stirrer; atomic absorption spectrophotometer (AAS); and reagents (phenolphthalein, methyl orange, sulphuric acid, potassium chromate, silver nitrate). The multi-parameter photometer kit is used to read several parameters in the fluid such as pH, temperature and EC, and it uses reagents for some of the tests. The drying oven heats, desiccates, and dries samples as

required. The glass wares examples used in this work include beakers, flasks, and graduated cylinders. Other apparatuses used in the experiment include stirring rod (for mixing chemicals); funnels (for passing materials through narrow openings); burettes (for dispersing precise amounts of liquid reagents); evaporating dishes (for holding liquid filtrate undergoing desiccation in drying ovens); filtration assembly (which is a glass set up having funnels and beakers used during filtration); electric weighing balance (used for measuring the weight samples and items); magnetic stirrer (used for spinning a magnetic stir bar immersed in a liquid); and atomic absorption spectrophotometer (AAS) (used for the quantitative determination of chemical elements). The reagents used in this research work were potassium chromate ($K_2Cr_2O_2$), silver nitrates ($AgNO_3$), phenolphthalein, methyl orange and sulphuric acid.

Water Analysis Procedure

The pH was determined electrometrically using a multiparameter photometer kit. First, the dipstick of the photometer was dipped into distilled water sample and the pH were read to confirm equipment calibration. The same was done for the extracted water samples A and B, respectively, to determine their pH values. For electric conductivity (EC) determination, a multiparameter photometer kit was also used. The procedure involved dipping the electronic dipstick into the water samples and reading the EC values. The two-extract water from samples were first diluted, because its electric conductivity was too high to be read. They were diluted using 99ml of distilled water in 1ml of the extract water, respectively. The electronic dipstick was dipped into diluted samples A and B and the electric conductivity was read. The total dissolved solids (TDS) were determined gravimetrically using evaporating dish, graduated cylinders, filtration assembly, drying oven and analytical balance. The samples were well stirred and 100ml volume was measured from each sample. The stirred sample were filtered using filter paper in a filtration assembly and the filtrate was collected into a weighed evaporating dish; and thereafter evaporated to dryness and dried to a constant weight at $180^\circ C$ after which the evaporating dish was measured. This procedure was taken for both samples respectively, with the TDS expressed as,

$$TDS \text{ (mg/L)} = \frac{(A-B) \times 1000}{V} \quad (1)$$

where A is the weight of the dried residue dish (mg), B is the weight of the dish (mg) and V is the volume of sample (mL).

The total suspended Solids (TSS) was determined gravimetrically using glass fibre filter papers, graduated cylinders, filtration assembly, drying oven and analytical balance with the step-by-step procedure involving drying and desiccating the filter paper at $105^\circ C$ and the initial weight of the filter paper was recorded. The 100mL of the stirred samples A and B were filtered using the dry filter paper in a filtration assembly respectively. The procedure was repeated for both samples with the TSS calculated as,

$$TSS \text{ (mg/L)} = (A-B) \times 1000/V \quad (2)$$

where A is the weight of the filtered and dried residue filter paper (mg), B is the weight of the dried filter paper (mg) and V is the volume of sample (mL).

The bicarbonate (HCO_3) level was determined through titration using glass ware and reagent. The procedure involved pouring 50 ml of water into a 150 ml beaker. Few drops of

phenolphthalein were added, and if a pink colour is produced, titrating with sulphuric acid, adding a drop every 2 or 3 seconds until the pink colour disappears to the colourless solution from this titration or to the original solution, is carried out. If no colour is produced with phenolphthalein, 1 or 2 drops of methyl orange is added. The titration continued without refilling the burette to the methyl orange end point and the total readings were noted. This parameter is calculated using,

$$HCO_3 \text{ (mg/L)} = \frac{1000 \times N(H_2SO_4) \times V_{acid}}{V_{sample}} \quad (3)$$

where $N(H_2SO_4)$ is the molarity of H_2SO_4 , V_{acid} is the volume of acid used and V_{sample} is the volume of sample.

Chloride determination was done through titration to check for the level of chloride content in each of the samples. Potassium chromate ($K_2Cr_2O_2$), and silver nitrates ($AgNO_3$) were used as reagents. 100ml of distilled water was turned into a flask labelled blank, which was used as a standard to check chloride content in samples A and B. 100ml of each of the samples were turned into different flasks labelled sample A and B, respectively. 1ml of potassium chromate ($K_2Cr_2O_2$), was added to all the samples using burette. 10ml of silver nitrate ($AgNO_3$) was slowly added to the blank sample in order to obtain a reddish-brown colour, at the point when the blank sample obtained this colour, addition of $AgNO_3$ was stopped. This was done for the remaining samples and results were calculated and recorded. For the calculations, we use,

$$Cl^- \text{ (mg/L)} = \frac{(A-B) \times 1000}{V}$$

where A is the volume of $AgNO_3$ used for titrating sample, B is the volume of $AgNO_3$ used for titrating blank, and V is the volume of sample

The heavy metal content in the samples were determined using an atomic absorption spectrophotometer (AAS). Hollow cathode lamps of each of the heavy metals were inserted in the AAS one after the other. The atomizer was lit with a match. The AAS was then calibrated using their specific constants. The tube in front of the atomizer was immersed in all the samples, and then the equipment absorbs the water samples and gives the concentration of metal in the sample. This was done for samples A and B.

B. Material Adsorption Treatment Plant

Different items and parts were used to setup the treatment plant. The items selected were carefully considered to ensure an effective treatment of produced water using activated carbon adsorption. The instruments and equipment used include the following: adsorbent (activated carbon – filter candles); sediment filter; filter bottles; pipes; feed tank; and fittings. The adsorbent used is activated carbon filters. The filter is in block candle of 10in height. The powdered activated carbon (PAC) filters have a filter size rated at 0.5 microns. A sediment filter was used within the treatment plant. The sediment filter has a height of 10in and a filter size rated at 10 microns. The Filter bottle are used to house and connect the activated filter candles to the flow line. They also control the waste water (produced) flow to ensure single flow and effective treatment. The pipes (PVC Pipes) are a key component of the treatment plant. Pipes are the channels through which the water flows. The filter bottles, ball valves and other components are connected along the pipes to form the treatment plant. One inch (1in) diameter

pipe was used for the work. For the purpose of this work is, a 20 litres plastic bucket was used as the produced water feed tank. Fittings were used to join pipes and connect other component to the flow line. The fittings used in this project work were: adapters, unions, M-F socket, ball valve, reducer and tap.

Adsorption Treatment Process

The adsorption system (Fig. 1) works as a continuous flow. The produced water flows from the feed tank through the ball valve into the sediment filter bottle. In this bottle, the first stage of treatment occurs removing the residue (particulate matter, sand, debris, etc.) and allowing the filtrate (water – still impure) through. The water then flows to the PAC filter bottle where all adsorbates (color, odor, Mg, Ca, etc.) are removed. Within the filter bottles, the flow is such that the influent from the feed tank enters the bottle around the filter, after which the water passes through to the middle of the filter undergoing filtration (at the sediment filter) and adsorption (at the PAC filter). To increase contact time and ensure a more effective treatment process, the flow rate was controlled using the ball valve flowing at about 20% flow capacity. The treated produced water was thereafter sampled and taken for analysis using the same methods and equipment discussed in section A.

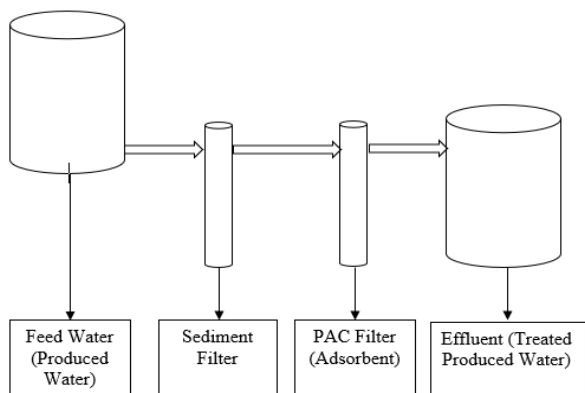


Figure 1: Treatment plant process flow chart.

III. RESULTS AND DISCUSSION

A. Produced Water Analysis

The produced water sampled from wells in Nembe, Bayelsa state, has analysis results as shown in table 1. The results show the different levels per parameter for the two oil wells sampled. Also, below are column charts showing the different parameter levels compared against Department of Petroleum Resources, DPR (currently called Nigerian Upstream Petroleum Regulatory Commission, NUPRC) stated standards.

pH Values

The degree of acidity or alkalinity of the water samples is determined using pH measurement. If the pH level falls out of the stated standard range, it can have adverse effects on the discharge environment including possible scale-formation or corrosion tendencies of the water (Breit et al., 1998). Drilling-mud filtrate, organic acids, such as acetic acid, or well-treatment chemicals can affect pH values. (Johnsen et al., 2004). Results obtained from Table 1 shows that the pH of

produced water obtained within the period under review for well B (7.46) was slightly higher than that of well A (7.42). However, both well samples meet DPR Specification (6.5 -8.5), as stated in the EGASPIN (Environmental Guideline and Standard for Petroleum Industries in Nigeria) report. is an arm of DPR (Department of Petroleum Resources) (EGASPIN, 2000).

TABLE 1: Produced water analysis results compared against DPR standards

ITEM NO.	PARAMETER	UNIT	READING		DPR STANDARD
			WELL A	WELL B	
A. Physico-Chemical					
1.	pH	-	7.42	7.46	6.5-8.5
2.	Total Dissolved Solid (TDS)	mg/L	12171.50	28016.80	<2000
3.	Total Suspended Solid (TSS)	mg/L	183.21	270.49	<50
4.	Electric Conductivity (EC)	µc/cm	39.50	35.10	-
5.	Bicarbonate (HCO ₃ ⁻)	mg/L	601.3	488.87	180-240
6.	Chloride (Cl ⁻)	mg/L	7149.07	18495.44	600
B. Toxins & Heavy Metals					
7.	Potassium (K ⁺)	mg/L	139.54	50.04	50
8.	Iron (Fe ²⁺)	mg/L	0.11	0.11	1.0
9.	Calcium (Ca ²⁺)	mg/L	85.40	88.49	75
10.	Magnesium (Mg ²⁺)	mg/L	54.94	25.40	30
11.	Sodium (Na ⁺)	mg/L	4631.80	9250.20	120

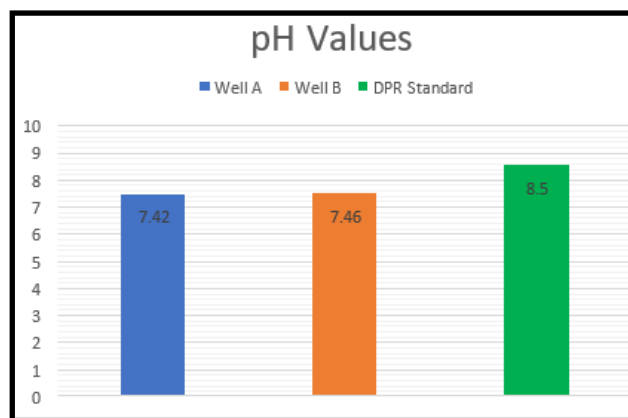


Figure 2: Measured pH Values of Produced Water.

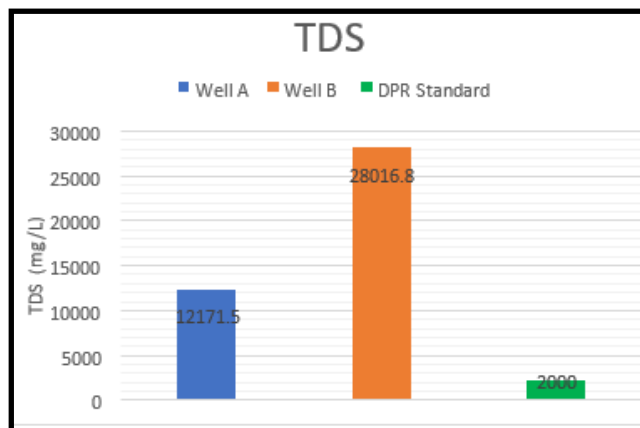


Figure 3: Total Dissolved Solids (TSS) Levels.

Total Dissolved Solids (TDS)

The TDS value shows the quantity of inorganic salts and

small organic matter that dissolved into the produced water. It is measured in mg/l or ppm. From Figure 3, the TDS value of the analyzed produced water sample for Well B (28016.8 mg/L) was much higher than that of Well A (12171.5 mg/L) and both values were well above the acceptable limit (2000 mg/L) of stated DPR standards.

Total Suspended Solids (TSS)

The TSS value shows the quantity of small solids in the produced water that did not settle out by gravity. It is measured in mg/L or ppm. From Figure 4, the TSS value of the analysed produced water sample for Well B (270.49 mg/L) was much higher than that of Well A (183.21 mg/L). Both values were higher than the acceptable limit (50 mg/L) of stated DPR standards.

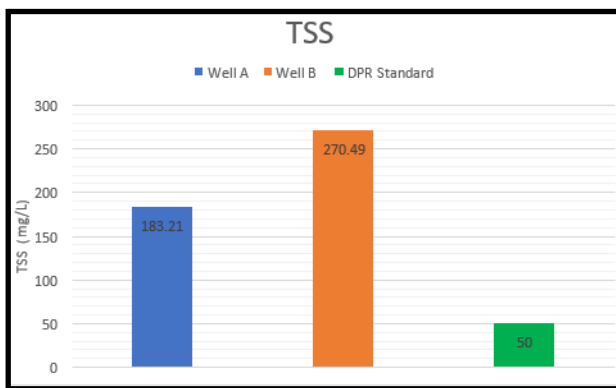


Figure 4: Total Suspended Solids (TSS) Levels of Produced Water.

Electric Conductivity (EC)

The EC value shows the ability of water to conduct electricity and this is dependent on the concentration of ions in the water. It is measured in $\mu\text{c}/\text{cm}$. From Figure 5, the EC value of the analysed produced water sample for Well A ($39.5\mu\text{c}/\text{cm}$) was slightly higher than that of Well B ($35.1\mu\text{c}/\text{cm}$).

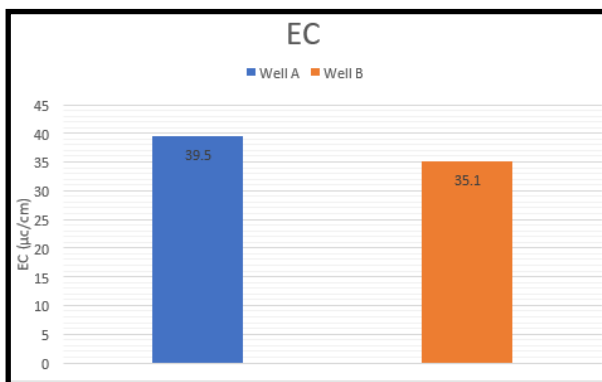


Figure 5: Electric Conductivity (EC) Measurement.

Bicarbonate (HCO_3) Levels

Bicarbonate in produced water increases the pH in produced water and they introduced from limestone in formations. It is measured in mg/L or ppm. From Figure 6, the HCO_3 value of the analyzed produced water sample for Well A (601.3 mg/L) was relatively higher than that of Well B (488.87 mg/L). Both

values were higher than the acceptable limit (240 mg/L) of stated DPR standards.

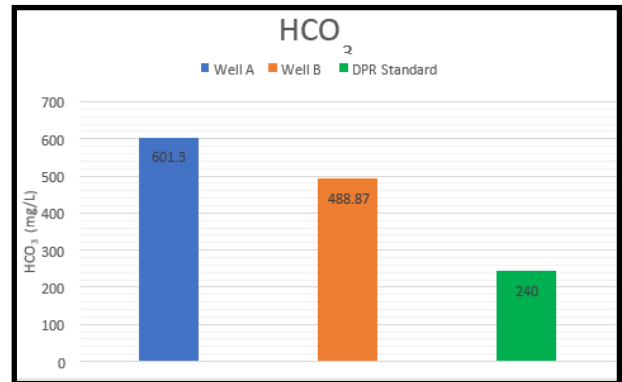


Figure 6: Bicarbonate Levels in produced water.

Chloride (Cl) Levels

This is the measure of chloride ions present in the produced water. It is measured in mg/L or ppm. From Figure 7, the Cl value of the analyzed produced water sample for Well B (18495.87 mg/L) was much higher than that of Well A (7149.07 mg/L) and both values were much higher than the acceptable limit (600 mg/L) of stated DPR standards.

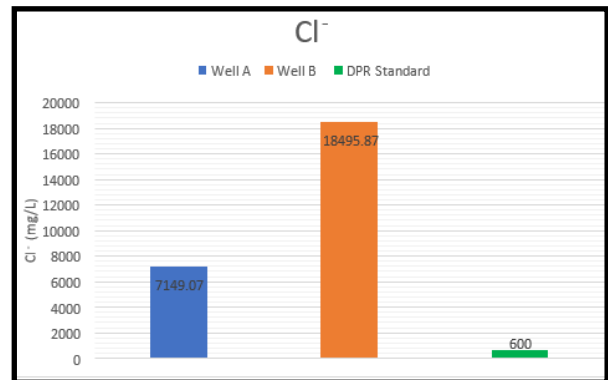


Figure 7: Chloride Levels in Produced Water.

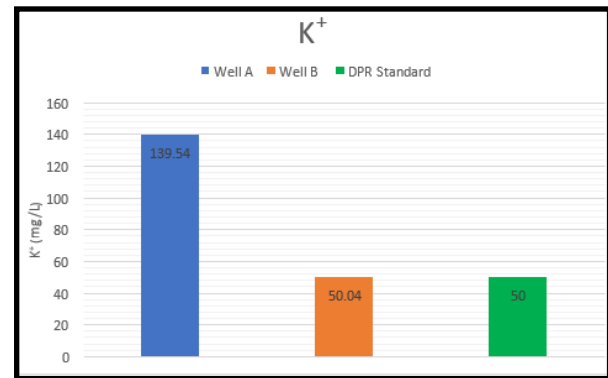


Figure 8: Potassium Levels in Produced Water.

Potassium (K^+) Levels

From Figure 8, the K^+ value of the analyzed produced water sample for Well A (139.54 mg/L) was much higher than that of Well B (50.04 mg/L). However, the potassium level of well B

was on the boundary of the acceptable limit while the level of well A was much higher than the acceptable limit (50 mg/L) of stated DPR standards

Iron (Fe^{2+}) Levels

From Figure 9, the Fe^{2+} level of the analysed produced water sample for Well A and Well B were the same (0.11 mg/L). The Fe^{2+} levels in both wells were within the acceptable limit (1.0 mg/L) of stated DPR standards.

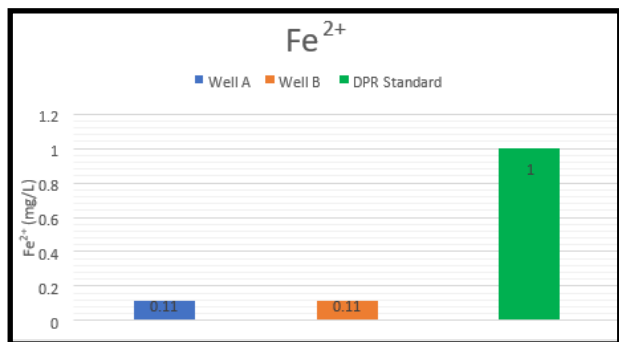


Figure 9: Iron Levels in Produced Water.

Calcium (Ca^{2+}) and Magnesium Levels

From Figure 10, the Ca^{2+} content of the analyzed produced water sample for Well B (88.49 mg/L) was slightly higher than that of Well A (85.4 mg/L). However, the calcium ion levels of both wells, were slightly higher than the acceptable limit (75 mg/L) of stated DPR standards. The Mg^{2+} levels in produced water sample for Well A (54.94 mg/L) was higher than that of Well B (25.4 mg/L). The magnesium ion level of well B was within the acceptable limit (see Figure 11) while the level of well A was higher than the acceptable limit (30 mg/L) of stated DPR standards.

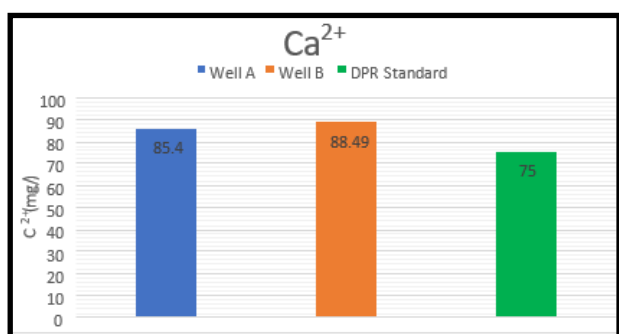


Figure 10: Calcium Levels in Produced Water.

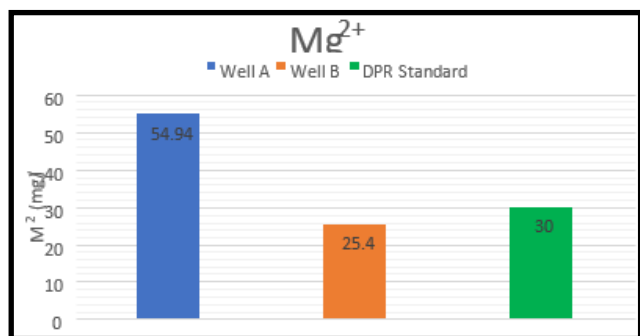


Figure 11: Magnesium Levels in Produced Water.

Sodium (Na^+) Levels

From Figure 12, the Na^+ level in produced water sample for Well B (9250.2 mg/L) was much higher than that of Well A (4631.8 mg/L) and both values were much higher than the acceptable limit (120 mg/L) of stated DPR standards. We observed that, during the experimental investigation, the produced water samples have a slightly tinted light brown colour oil films with slight emulsion

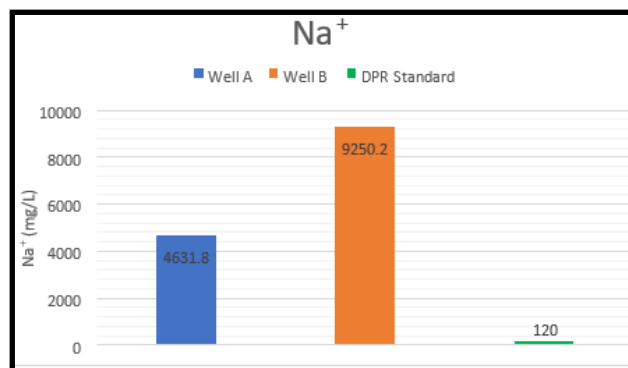


Figure 12: Sodium Levels in Produced Water.

B. Treated Produced Water Analysis

The produced water sampled from wells in Nembe, Bayelsa state, was treated using a sediment filter and activated carbon adsorption. The treatment effluent has analysis results shown in Table 2. The column charts (see Figures presented in this section) shows the different parameter levels for the produced water compared against the treated samples and DPR stated standards.

TABLE 2: Treated produced water analysis results compared against DPR standards

ITEM NO.	PARAMETER	UNIT	READING		DPR STANDARD
			WELL A	WELL B	
A. Physico-Chemical					
1.	pH	-	7.49	7.51	6.5-8.5
2.	Total Dissolved Solid (TDS)	mg/L	12051.95	27120.03	<2000
3.	Total Suspended Solid (TSS)	mg/L	49.47	69.03	<50
4.	Electric Conductivity (EC)	µc/cm	36.49	33.70	-
5.	Bicarbonate (HCO_3)	mg/L	599.40	487.32	180-240
6.	Chloride (Cl^-)	mg/L	7112.70	18432.21	600
B. Toxins & Heavy Metals					
7.	Potassium (K^+)	mg/L	111.63	42.04	50
8.	Iron (Fe^{2+})	mg/L	0.04	0.05	1.0
9.	Calcium (Ca^{2+})	mg/L	71.22	73.79	75
10.	Magnesium (Mg^{2+})	mg/L	30.31	17.59	30
11.	Sodium (Na^+)	mg/L	4206.21	8787.69	120

pH Values of Treated Produced Water

From Figure 13, the pH value of the treated produced water samples was slightly higher than the untreated sample for both wells. However, the pH values for all samples (treated and untreated) were within the acceptable range (6.5-8.5) of stated DPR standards.

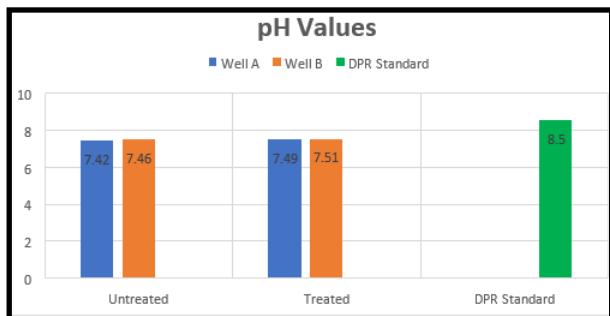


Figure 13: pH Values of Treated and Untreated Produced Water

Total Dissolved Solids (TDS) of Treated Produced Water

From Figure 14, the TDS levels of the treated produced water samples was slightly lower than the untreated sample for both wells. The TDS levels for all samples (treated and untreated) were significantly higher than the acceptable limit of stated DPR standards. The treatment process did not have any significant impact on the TDS levels.

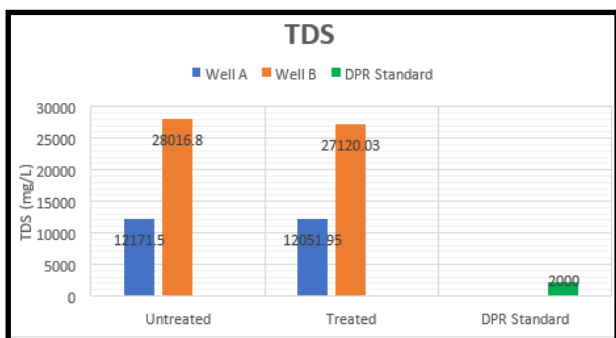


Figure 14: Total Dissolved Solids Levels in Treated Produced Water.

Total Suspended Solids (TSS) in Treated Produced Water

From Figure 15, the TSS value of treated produced water sample showed significant reductions when compared against the untreated water levels; with the TSS level reducing from 183.21 to 49.47 mg/L for well A and 270.49 to 69.03 mg/L for well B. Well B has TSS levels relatively higher than the acceptable limit (50 mg/L) of stated DPR standards.

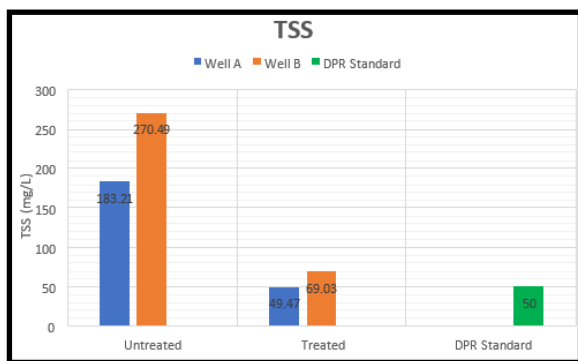


Figure 15: Total Suspended Solids Levels

Electric Conductivity (EC)

From Figure 16, the EC value of the treated produced water samples show a slight reduction in the conductivity. This can

result from the reduction of reduced salt and heavy metal ions as a result of the treatment process.

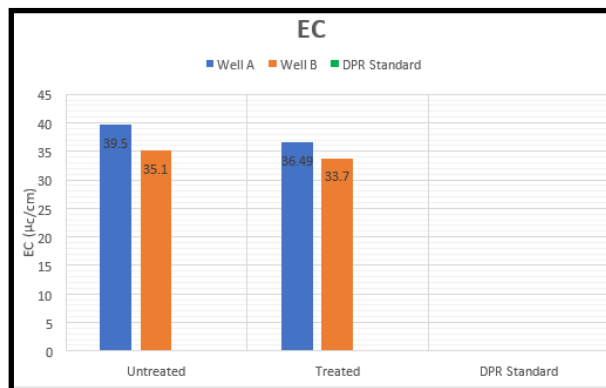


Figure 16: Electric Conductivity of Treated Produced Water

Bicarbonate (HCO₃) and Chloride (Cl⁻)

The HCO₃ levels of the treated produced water samples was identical to the untreated produced water (see Figure 17). Hence, all values were higher than the acceptable limit (240 mg/L) of stated DPR standards. This shows that the treatment process had no effect on the HCO₃ levels. Figure 18 shows that the chloride ion content of treated produced water samples has no significant changes. All values were much higher than the acceptable limit (600 mg/L) of stated DPR standards.

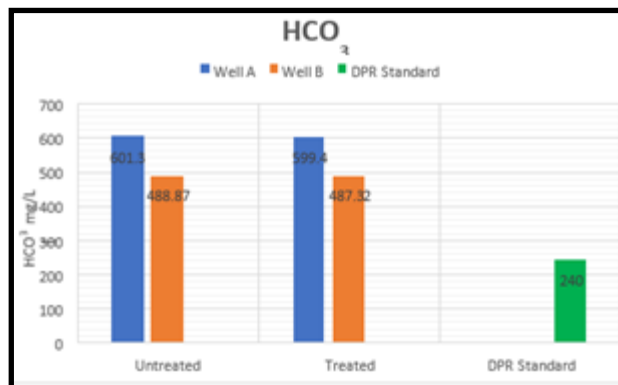


Figure 17: Bicarbonate Levels in Treated Produced Water.

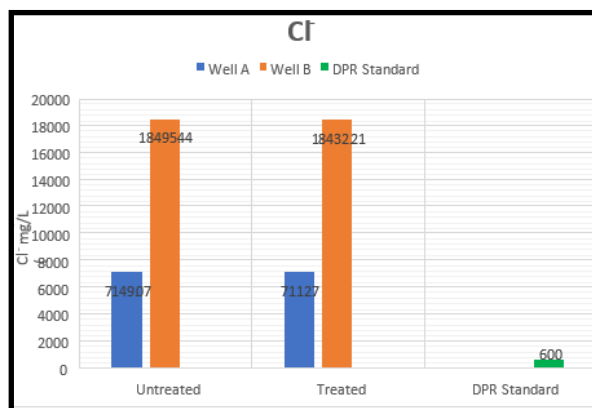


Figure 18: Chloride Levels in Treated Produced Water

Potassium (K⁺) Levels in Treated Produced Water

From Figure 19, the K^+ value of the treated produced water sample for Well A reduced from 139.54 to 111.63 ppm while that of well B reduced from 50.04 to 42.04 mg/L. The potassium level of well A was still higher than the acceptable limit (50 mg/L) of stated DPR standards.

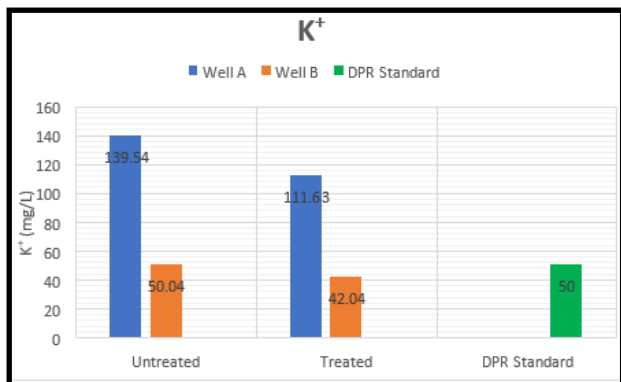


Figure 19: Potassium Levels in Treated Produced Water.

Iron (Fe^{2+}) Levels in Treated Produced Water

The Fe^{2+} levels in treated produced water sample for Well A and Well B reduced (Figure 20). The Fe^{2+} levels in both wells were within the acceptable limit (1.0 mg/L) of stated DPR standards.

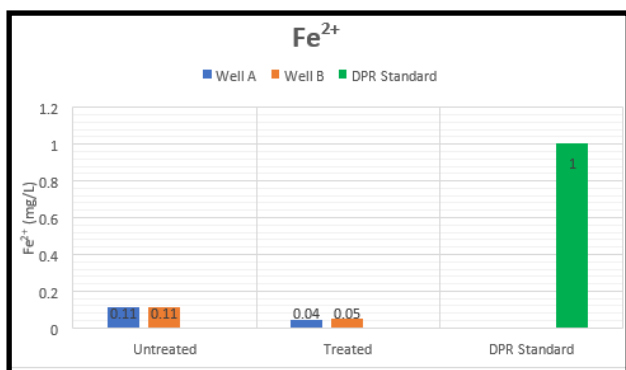


Figure 20: Iron Levels in Treated Produced Water.

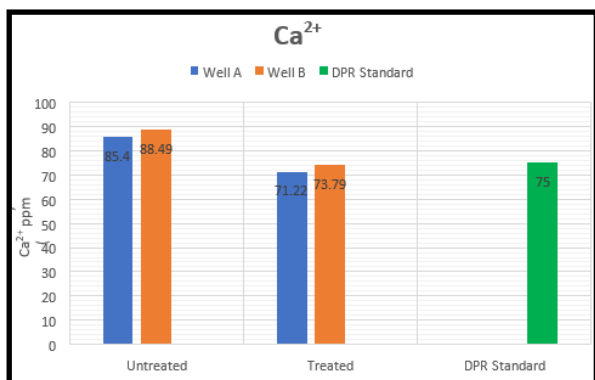


Figure 21: Calcium Levels in Treated Produced Water.

Calcium (Ca^{2+}) and Magnesium (Mg^{2+}) Levels

From Figure 21, the Ca^{2+} level in treated produced water samples for both wells showed reductions. After undergoing

treatment, the Ca^{2+} levels of both wells, were within the acceptable limit (75 mg/L) of stated DPR standards. From Figure 22, the Mg^{2+} level for both Wells showed significant reductions but were both within the acceptable limit (30 mg/L) of stated DPR standards

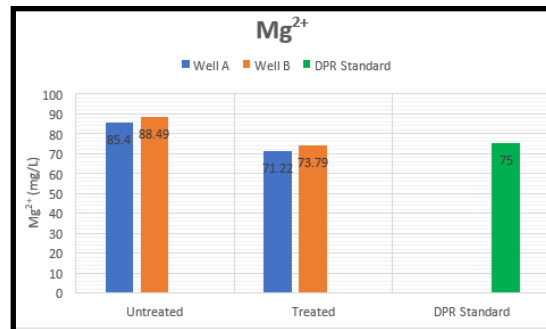


Figure 22: Magnesium Levels in Treated Produced Water.

Sodium (Na^+) Levels

The Na^+ level in treated produced water reduced from 4631.80 mg/L to 4206.21 mg/L for well A and from 9250.20 mg to 8787.69 mg/L for well B, respectively. The sodium ion levels of both wells were still much higher than the acceptable limit (120 mg/L) of stated DPR standards.

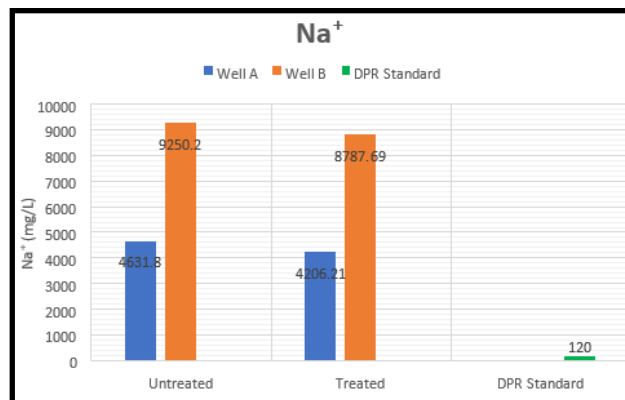


Figure 23: Sodium Levels

IV. CONCLUSION

Results show that physiochemical parameters of produced water samples from Nembe in Bayelsa State are higher than the acceptable regulatory limit for discharge to the environment and activated carbon adsorption can be used to detoxify and manage produced water. The activated carbon-based adsorber shows some level of effectiveness in handling suspended solids (e.g. heavy metals) but showed some difficulty in handling dissolved solids (e.g. salt ions, chloride and bicarbonates”.

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