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Impact analysis of pollutants in produced water

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Abstract

Produced water was treated to Nigerian Federal Environmental Protection Agency (FEPA) discharge limits using the concept of substrate limiting thermophilic anaerobic digestion with physical adsorption. The percentages of pollutants removed from the produced water shows that the treatment efficiency was approximately 100 % and the percentage error approximately 0 %. The concentration of Total Suspended Solids (TSS) in the produced water was found to be the most potential among the pollutants in the produced water for having a coefficient of variation of 0.998 (99.8 %) followed by Biochemical Oxygen Demand (BOD); Total Dissolved Solids (TDS); Total Hydrocarbon Content (THC); Concentration of oil and Grease (COG); negative of the logarithm of Hydrogen ion concentration (pH) and concentration of Volatile Suspended Solids (VSS) with Coefficients of Variation 0.930; 0.709; 0.380; 0.331; 0.087 and 0 respectively. This shows that the concentration of Total Suspended Solids (TSS) in the produced water is the furthest away from the Nigerian FEPA discharge limit and hence the highest contributor to the pollutant level of the produced water. More so, most suspended solids in the produced water are the most toxic and hence the major aspect in the treatment of produced water is the efficiency in the removal of suspended solids whether by filtration or adsorption. Produced water must therefore be treated so as to remove the Total Suspended Solids, Biochemical Oxygen Demand, Total Dissolved Solids, Total Hydrocarbon Content, Oil and Grease, pH, Volatile Suspended Solids to the discharge limits recommended by the Nigerian Federal Environmental Protection Agency (FEPA) before discharge into the environment (land and/or water bodies) so as to safeguard the environment and ecosystem.

Keywords: produced water; total suspended solids; federal environmental protection agency; discharge limits; potential pollutant; coefficient of variation

1. Introduction

Produced water is water that comes out of the well with crude oil during crude oil production. Produced water contains soluble and non-soluble oil/organics, suspended solids, dissolved solids and various chemicals used in the production process (WEF, 2021) ^[9]. Produced water is mixed with suspended and/or dissolved solids and needs to be treated so as to remove these solids, hydrocarbons, oil and grease and other toxic and hazardous substances present in the produced water. Produced water is a term used in the oil industry to describe water that is produced as by-product during extraction of oil and natural gas. Produced water are a kind of brackish and saline waters from underground formation that are brought to the surface (Wikipedia, 2021) ^[11]. Currently, majority of the produced water is managed by disposing of it using a practice known as underground injection where that water can no longer be accessed or re-used. This could lead to potable water scarcity in some parts of some countries as the drinking water in some parts of some countries is the treated produced water discharged from a nearby community yesterday or a day before. Renee Cho (2011) ^[5] stated that in parts of some countries treated produced water have been re-used as drinking water. Chemical and/or physical purification is carried out after a period of natural purification process in the groundwater or reservoir. Purified Produced water is safe and clean and help ease water shortages.

The Nigerian Federal Environmental Protection Agency (FEPA) (2002) provides discharge limits for treated produced water which is to be discharged into the environment (land or water bodies). In Nigeria, the treatment of produced water to the discharge limits stipulated by FEPA imposes a major challenge to the oil and gas industry. The contribution of each pollutant in the produced water to the toxicity of the produced water needs to be known so that their removal can be targeted so as to enhance optimum results. To know the target pollutants, an impact analysis is necessary.

Wikipedia (2019) ^[10] defined impact analysis as the recording, examining and evaluating the results of a process operation. Impact analysis is a method of measuring outcomes to know their effects. Impact analysis helps determine which among several alternatives the most effective approach is. It is important to address impact evaluation as part of an integrated monitoring, evaluation and research plan. The aim of this study is to find the most potential pollutant among the key pollutants in produced water by carrying out an impact analysis using statistical methods based on the Nigerian Federal Environmental Protection Agency (FEPA) discharge limits. Under substrate limiting anaerobic digestion treatment of the produced water with physical adsorption, this research studies the effects of key physico-chemical parameters of produced water treatment e.g. Biochemical Oxygen Demand (BOD); Total Hydrocarbon Content (THC); Concentration of Oil and Grease (COG); Negative of the Logarithm of Hydrogen ion Concentration (pH); Concentration of Volatile Suspended Solids (VSS); Concentration of Total Suspended Solids (TSS) and Concentration of Total Dissolved Solids (TDS) so as to determine by statistical analysis the most potential among them based on discharge limits stipulated by the Nigerian Federal Environmental Protection Agency (FEPA).

2. Materials and Methods

2.1. Materials Used for the Research

The following materials were used for the research: Produced water collected from reserve pit of Ebocha oil field, Agip Oil Company, Omoku, Rivers State, Nigeria.

Perkins Emma Laboratory standby electrical power generator, Petri dishes, 200 mL conical flask, pipette, bent glass rod, spreader, test tubes, chemical weighing balance, porcelain evaporating dish, crucible tongs, desiccators, porcelain crucible, 100 mL beaker, 100 mL volumetric flask, dissolved oxygen reagent bottles, mineral water, 25 mL density bottle, Hanna pH meter H196107, Hanna

conductivity meter, stirring rod, microscopic glass slide, durhan tubes, sterile hockey, muffle furnace LMF4, Jenway 6305 UV/visible spectrophotometer, Erlenmeyer flask, oven, anaerobic incubator, autoclave, labtech anaerobic jar, olympus microscope, Microbalance, Hewlett Packard (HP) 5890 series II GC with FID, GBC Avanta atomic absorption spectrophotometer, electrical hot plate, bunsen burner, Thermophilic bacteria (*Bacillus stearothermophilus*) isolated from the produced water, *Methanogenic* bacteria (*Methanobrevibacter*) isolated from *bos taurus* intestine with the help of Olympus microscope and spatula and stored in glycerine. Oxoid Anaero Gen TM AN 0035A gas pack used in labtech anaerobic Jar to create anaerobic condition, chloroform, mineral salt water, starch indicator, Winkler reagent A & B, concentrated Sulphuric acid, 0.025 N sodium thiosulphate, amberlite, sugar cane baggase, charcoal, zeolite, activated alumina, distilled water, tissue paper, filter Paper, activated carbon, silica gel, nutrient agar (LAB M), physiological saline, rubber hose, hydrogen peroxide, ethanol, sufranin, Simmons citrate agar, alpha naphthol, potassium hydroxide, methyl red, ashless filter paper and dichloromethane.

2.2. Methods

The values of physico-chemical parameters for the raw untreated produced water obtained from the reserve pit of Ebocha Oil Field, Omoku, Rivers State, Nigeria were obtained by laboratory analysis. The produced water was treated to Nigerian Federal Environmental Protection Agency (FEPA) discharge limits using the concept of substrate limiting thermophilic anaerobic digestion with physical adsorption. Results for mesophilic (28 – 37 °C) and thermophilic (55 – 75 °C) conditions were compared and thermophilic condition results chosen for the impact analysis as it enhances higher reaction rates, increases death rate of pathogens and hence more produced water can be treated in a shorter time. This helps avoid the problem of accumulation of the produced water which is an environmental disaster. USEPA (2019) classified both mesophilic and thermophilic digestion as Processes to Further Reduce Pathogens (PFRP). Applying substrate limiting thermophilic anaerobic digestion with physical adsorption as the research concept, the Nigerian Federal Environmental Protection Agency (FEPA) discharge limits were used as reference bounds (research basis) for the treatment of the wastewater. The experimental set-up was as shown in the figure below:

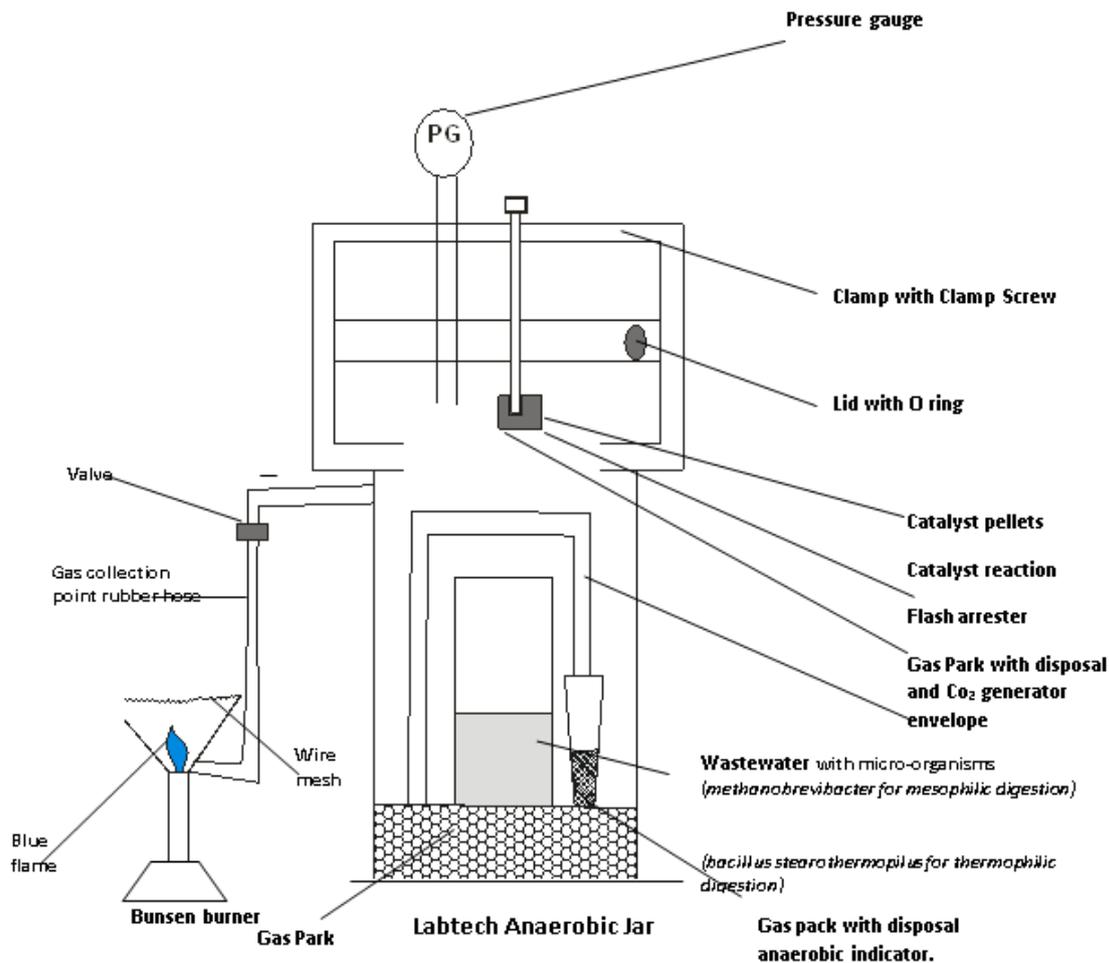


Fig 1: Experimental Set-up for Microbial Digestion of the Produced Water

Samples of the digested produced water were taken for laboratory experimental tests for a hydraulic retention time of 5 days, the number of days taken to attain FEPA discharge limits. Using *Bacillus Stearo - thermophilus* isolated from a sample of the produced water as the thermophilic bacteria and *Methanobrevibacter* isolated from *bos taurus* intestine as the mesophilic bacteria, the following experiments were carried out:

a. Isolation and Identification of Bacteria

A ten-fold serial dilution was carried out using physiological saline after which the diluent streaked with nutrient agar was inoculated or cultured in culture plates for growth of the micro-organism in anaerobic jar with gas pack and catalyst. This was incubated for 3 days at 37 °C for mesophiles and 75 °C for thermophiles. Biochemical tests were carried out to identify the micro-organism followed by enumeration of colonies on plates. The isolated micro-organism was used to digest the produced water.

b. Measurement of Percent Volatile Suspended Solids (VSS) in the Produced Water

An ashless filter paper was dried in an oven at 105 °C and cooled in the desiccator and weighed. The weight was

recorded. The sample was filtered through the filter paper, dried in the oven and re-weighed.

The residue was burned in the Muffle furnace in the porcelain evaporating dish which was previously weighed. The remnant of the weighed residue was cooled to room temperature and weighed and % VSS calculated using equation (1) as in Japhet (2020) [3].

$$\% \text{ Volatile Suspended solids} = \frac{\text{Weight of Volatile residue}}{\text{Weight of residue}} \times 100 \quad (1)$$

c. Measurement of Concentration of Total Suspended Solids (TSS) in the Produced Water

An ashless filter paper was dried in an oven to a constant weight. The weight of the filter paper was recorded. 100 mL of the produced water sample was measured. The filter paper was folded into a glass funnel and the 100 mL of produced water poured into the filter paper until all was filtered through. The filter paper was dried at 105 °C to eliminate all the water present. The residue was cooled to room temperature and then re-weighed in the same analytical balance. The concentration of Total Suspended Solids (TSS) was calculated using equation (2) as in Japhet (2020) [3].

$$\frac{\left[\begin{array}{c} \text{Weight} \\ \text{of} \\ \text{filter paper} \\ \text{with residue} \end{array} \right] - \left[\begin{array}{c} \text{Weight} \\ \text{of} \\ \text{filter paper} \end{array} \right] \times \left[\begin{array}{c} \text{Conversion factor} \\ \text{from} \\ \text{gram to miligram} \end{array} \right]}{\text{Volume of produced water sample filtered (mL)}} \times \left[\begin{array}{c} \text{Conversion} \\ \text{factor} \\ \text{from} \\ \text{millilitre to litre} \end{array} \right] \quad (2)$$

d. Measurement of Concentration of Total Dissolved Solids (TDS) in the Produced Water

A dried empty evaporating flask was weighed and the weight recorded. A volume of sample of the produced water was measured and put into the evaporating flask. The flask containing the produced water was heated to evaporate out

the water leaving behind the residue. The flask with the residue was weighed and the weight of the flask subtracted from it to find the weight of the residue. The concentration of dissolved solids in the produced water sample was calculated using equation (3) as in Japhet (2020) [3].

$$\frac{\left[\begin{array}{c} \text{Weight} \\ \text{of} \\ \text{flask} \\ \text{with residue} \end{array} \right] - \left[\begin{array}{c} \text{Weight} \\ \text{of} \\ \text{empty flask} \end{array} \right] \times \left[\begin{array}{c} \text{Conversion factor} \\ \text{from} \\ \text{gram to miligram} \end{array} \right]}{\text{Volume of sample used}} \times \left[\begin{array}{c} \text{Conversion} \\ \text{factor} \\ \text{from} \\ \text{millilitre to litre} \end{array} \right] \quad (3)$$

American Public Health Association Standard Methods (1998) classified the solids contained in the filtrate that passes through a filter with nominal pore size of 2.0 micrometer or less as dissolved. The solids captured on the filter are called Suspended Solids.

e. Measurement of Total Hydrocarbon Content (THC) of the Produced Water

100 mL of produced water was measured into a 250 mL separatory flask. 10 mL of chloroform was added and the flask shaken vigorously. The separatory flask was kept on a

retort stand after the agitation. The chloroform layer (bottom layer) was released into a clean test tube and anhydrous sodium sulphate added to remove traces of moisture from the extract. The clean solution was read at 420 nm in a Jenway 6305 UV visible spectrophotometer and the resultant absorbance was recorded.

A graph of concentration versus absorbance for a standard (1:1) Bonny light/medium petroleum crude oil was plotted and the gradient of the graph recorded. The total hydrocarbon content of the produced water was calculated using equation (4) as in Japhet (2020) [3].

$$\left[\begin{array}{c} \text{Gradient of a} \\ \text{Standard (1:1)} \\ \text{Bonny Light/Medium} \\ \text{Petroleum crude oil versus} \\ \text{its absorbance} \end{array} \right] \times \left[\begin{array}{c} \text{Absorbance of} \\ \text{prod. water} \\ \text{sample} \end{array} \right] \times \left[\begin{array}{c} \text{Dilution} \\ \text{factor} \end{array} \right] \times \frac{\left[\begin{array}{c} \text{Volume of Chloroform} \\ \text{used} \\ \text{for extraction (mL)} \end{array} \right]}{\left[\begin{array}{c} \text{Volume of Extract (mL)} \end{array} \right]} \quad (4)$$

f. Measurement of Concentration of Oil and Grease in the Produced water

The produced water sample was extracted using hexane. The organic phase of the extract was drained through an analytical funnel containing filter paper and 10 g of anhydrous sodium moistened with n-hexane and collected in an Erlenmeyer flask. The flask with the extract was then placed over a stirrer plate and the colour observed. The Erlenmeyer flask was then placed under magnetic stirring for 6 minutes with 3.0 g of

silica gel as the adsorbent. The extract was filtered and collected in a previously weighed round – bottomed distillation flask placed in a IKA RV-5 Basic 1 – B rotary evaporator to remove the solvent, after which the remaining sample was left for one hour under nitrogen flow. The flask was then re-weighed. At the end of the extraction, the total oil and grease content was calculated using equation (5) as in Japhet (2020) [3].

Total oil and Grease (TOG) =

$$\frac{\left[\begin{array}{c} \text{Mass of flask} \\ \text{and} \\ \text{its contents} \\ \text{in grams} \end{array} \right] - \left[\begin{array}{c} \text{Mass of} \\ \text{empty} \\ \text{flask} \\ \text{in grams} \end{array} \right] \times \left[\begin{array}{c} \text{Conversion} \\ \text{factor from} \\ \text{gram to} \\ \text{miligram} \end{array} \right]}{\left[\begin{array}{c} \text{Volume of} \\ \text{prod. water} \\ \text{sample} \\ \text{analysed in mL} \end{array} \right]} \div \left[\begin{array}{c} \text{Conversion} \\ \text{Factor} \\ \text{from} \\ \text{mL to Litre} \end{array} \right] \quad (5)$$

c. Measurement of Biochemical Oxygen Demand (BOD) in the Produced water

100 mL produced water was measured into a clean beaker and 200 mL of mineral water from the reagent dissolved oxygen bottle introduced into the produced water. This was stirred to disperse the produced water and obtain a homogenous mixture. The mixture was re-introduced into two dissolved oxygen reagent bottles filled to the brim which

had previously been used to measure out the mineral water. The bottles were capped tightly with appropriate cork and the cork was removed and 0.5 mL Winkler A & B reagent pipetted into the reagent dissolved oxygen bottle respectively. The reagent bottle was re-corked and inverted gently for about three times and allowed to stand to sediment the precipitated components.

The reagent dissolved oxygen bottle was carefully opened and about 2 mL concentrated sulphuric acid was added,

recapped and inverted gently and carefully thrice for the Precipitate to dissolve completely. 25 mL of this solution was titrated with 0.025 N Sodium thiosulphate using starch as indicator near the end point. The volume of the Sodium thiosulphate that was utilized to obtain colour change was recorded as the titre value.

The other reagent bottle containing the second batch of produced water and mineral salt water solution was placed in an incubator for 5 days and at the end dissolved oxygen analysis was carried out. The titre value of this batch was recorded and the titre at the fifth day. The BOD value was calculated using equation (6) as in Japhet (2020) [3].

$$BOD_5 = \frac{DO_{initial} - DO_{Final}}{DilutionFactor} \quad (6)$$

d. Measurement of the Negative of the Logarithm of Hydrogen Ion Concentration (pH)

The electrode of the Hanna pH meter H196107 was dipped into the produced water in a beaker. Fluctuating readings were displayed until a steady reading was displayed. The steady reading was recorded as the pH of the produced water sample. This pH of the produced water was raised to neutral pH of 7.0 by drop wise addition of sodium hydroxide to the produced water with measurement of the pH per drop addition until a neutral pH of 7.0 was obtained.

e. Measurement of Concentration of Heavy Metals in the Produced water

The produced water was prepared for metal ion analysis by acidification with 1 mL concentration hydrochloric acid. The wavelength of the GBC avanta atomic absorption spectrophotometer was selected to that of the metal whose concentration was to be measured. The air and acetylene flows were adjusted to give optimum flame condition and the hollow cathode lamp given adequate time to stabilize. The produced water sample solution was aspirated into the flame of the GBC avanta atomic absorption spectrophotometer under the same condition as the standards. A calibration curve was plotted from standard range after setting the top standard to a suitable scale deflection and the 0 PPM standard

$$\left[\frac{\text{Gradient of conc versus absorbance graph}}{\text{Absorbance of the produced water sample}} \right] \times \left[\frac{\text{Conversion Factor}}{\text{from mL to L}} \right] \quad (7)$$

b. Measurement of Concentration of Nitrogen in the Produced Water

A volume of produced water sample was measured and titrated against hydrochloric acid and the titre value recorded at the end point as detected by a colour change to purple. Boric acid and the indicator gave purple colour but when free ammonia was introduced, the colour change to green which

$$\frac{\left[\frac{\text{volume of Produced water}}{\text{Titre Value}} \right] \times \left[\frac{\text{Conversion factor}}{\text{from ML to Liter}} \right]}{\left[\frac{\text{Volumetric equivalent used in relation of Nitrogen}}{\text{of Nitrogen}} \right] \times \left[\frac{\text{Total Volume of Produced water digest}}{\text{Produced water digest}} \right]} \quad (8)$$

h. Removal of Nutrients from the Produced Water

A sample of the produced water was poured into a column filled with activated alumina which adsorbed phosphorus from the produced water. The produced water from this column was poured into a second column filled with zeolite.

to zero. The blank values were subtracted and corrected to dry weight values and the metal concentrations read from a printout obtained from the spectrophotometer.

f. Measurement of the Concentration of Polycyclic Aromatic Hydrocarbons in the Produced Water

250 mL of produced water sample was measured into a separatory funnel. 25 mL of dichloromethane was added to the produced water sample in the separatory funnel. The mixture was shaken vigorously so as to form an organic solvent extract which was passed through a column containing cotton wool, silica gel (to prevent passage of debris from the extract) and anhydrous sodium sulphate (to remove moisture from the extract) into a receiving container. 1 µL sample of the organic extract collected in the receiving container was injected by means of a hypodermic syringe through a rubber septum into the column of the Hewlett Packard (HP) 5890 series II Gas Chromatography (GC) equipment incorporated with a Flame Ionization Detector (FID). The vapour compositions were detected by the FID as Polycyclic Aromatic Hydrocarbons (PAHs) as the vapour emerged from the column. The concentration of each polycyclic aromatic hydrocarbon was recorded in mg/L or PPM.

g. Measurement of Concentration of Nutrients in the Produced Water

a. Measurement of Concentration of Phosphorus in the Produced Water

10 mL of a sample of produced water was weighed and the weight recorded. The sample was put into the sample compartment of a Jenway 6305 UV visible spectrophotometer and the absorbance recorded. A standard graph of concentration of a standard sample of potassium dihydrogen orthophosphate (KH₂PO₄) versus absorbance was plotted and the gradient of the graph recorded. The product of the gradient of this graph and the absorbance of the produced water sample gave the concentration of phosphorus in the produced water sample. The concentration of phosphorus in the produced water sample was calculated using equation (7) as in Japhet (2020) [3].

on titrating with 0.1 M HCl returned to purple at the end point. The volume equivalent of the titre value is relation to nitrogen was calculated and the total volume of produced water and hydrochloric acid mixture measured and recorded. The concentration of nitrogen in the form of free ammonia in the produced water was calculated using equation (8) as in Japhet (2020) [3].

The zeolite adsorbed nitrogen from the produced water. The produced water from this column was poured into a third column filled with activated carbon. The activated carbon adsorbed potassium from the produced water.

i. Removal of Solids and Organic Matter from the Produced Water

The produced water sample was passed through a filter which separated the suspended solids from the produced water which was then passed through a column filled with activated charcoal. The activated charcoal adsorbed dissolved solids as well as organic matter from the produced water.

j. Removal of Hydrocarbons from the Produced Water

The produced water was poured into a column filled with amberlite. The amberlite adsorbed the Polycyclic Aromatic Hydrocarbons (PAHs) from the produced water. The resultant produced water was then poured into another column filled with sugarcane baggase. The sugarcane baggase adsorbed hydrocarbons from the produced water.

k. Removal of oil and Grease from the Produced Water

Oil and grease floating on top of the produced water was decanted from the produced water after which it was poured into a column filled with silica gel. The silica gel adsorbed oil and grease from the produced water.

l. Removal of Heavy Metals including Potassium from the

Produced Water

The produced water was poured into a column filled with granular activated carbon. The activated carbon adsorbed heavy metals from the produced water. Potassium is removed along with heavy metals because Potassium is a nutrient just like nitrogen and phosphorus that contributes to eutrophication of the water body. Sampson (2022) [6] defined Eutrophication as a condition of excessive growth of algae and other aquatic plants in a water body. This causes deterioration of the water quality.

m. Measurement of Percentages of Pollutants Removed

The mass of pollutants at the inlet of each adsorber were obtained using mass balances originating from laboratory data. The FEPA discharge limits which were attained were used to obtain the mass of pollutants at the outlet of each adsorber. The percentages of pollutants removed were calculated using the equations (9):

Percentages of Pollutants Removed =

$$\frac{\text{Amount Removed}}{\text{Total Amount}} \times \frac{100}{1} \quad (9)$$

$$\equiv \frac{\left[\frac{\text{Initial Concentration of Pollutant}}{\text{in the untreated Produced water}} \right] - \left[\frac{\text{Final Concentration of Pollutant in Treated Prod. water}}{\text{in the raw untreated Produced water}} \right]}{\left[\frac{\text{Initial Concentration of Pollutant}}{\text{in the raw untreated Produced water}} \right]} \times \frac{100}{1} \quad (10)$$

$$\% \text{ Error} = \frac{\left[\frac{\text{FEPA discharge limit}}{\text{limit}} \right] - \left[\frac{\text{Final Concentration of Pollutant in Treated produced water}}{\text{FEPA discharge Limit}} \right]}{\left[\frac{\text{FEPA discharge Limit}}{\text{limit}} \right]} \times \frac{100}{1} \quad (11)$$

n. Statistical Method for Impact Analysis of Pollutants in Produced Water

Dispersion measure of the physico-chemical parameters of anaerobic digestion treatment of produced water was computed from FEPA discharge limits (Assumed Mean). The standard deviation of each of the physico-chemical parameters were divided by the real mean of the physico-chemical parameters to obtain the coefficient of variation of each of the physico-chemical parameter. The parameter with

the highest coefficient of variation was considered to be the highest contributor to the pollutant level of the produced water and hence the most impactful. The higher the coefficient of variation, the further away the parameter is from the FEPA discharge limit (Assumed Mean) and hence the higher the contribution of the parameter to the toxicity of the produced water. The coefficient of variation is given by the ratio of the standard deviation to the real mean as in the equation (14):

$$\text{Real Mean} = \frac{\text{Summation of Experimental Results of each Parameter}}{\text{Number of Experiments}} \quad (12)$$

$$\text{Standard Deviation} = \frac{\frac{\text{Suare Root of Summation of [parameter-Assumed Mean]}^2}{\text{Number of Tests}} - \text{Square Root of Summation of [Parameter-Assumed Mean]}^2}{\text{Number of Tests}} \quad (13)$$

$$\text{Coefficient of Variation} = \left[\frac{\text{Standard Deviation of each Parameter}}{\text{Real Mean of each Parameter}} \right] \quad (14)$$

3. Results and Discussion

a. Results of Biochemical Tests

The results of Biochemical tests for Mesophilic Microorganisms indicated Methanogenic *methanobrevibacter* as acid production indicated a colour change from red to yellow and gas production indicated in space in the durhan tubes in sugar fermentation tests. Effervescence occurred in catalase tests, red colour in gram staining, colour change from green to blue in citrate utilization test and acid production in mortility test.

The results of Biochemical tests for thermophilic micro-organism indicated *Bacillus Stearothermophilus* as besides that acid production indicated a colour change from red to yellow and gas production indicated in space in the durhan tubes in sugar fermentation test, the endospores were stained green in spore test. More so, Gram staining showed purple stain, Mortility test gave pink colour and starch hydrolysis test showed a clear zone around the bacterial growth after addition of iodine to the agar.

a. Biochemical Oxygen Demand

Table 1: Biochemical Oxygen Demand

Day	Mesophilic (mg/L)	Thermophilic (mg/L)
1	2,784.0	-
1.5	-	-
2.0	720.0	240.0
2.5	560.0	200.0
3.0	150.0	100.0
3.5	120.0	84.0
4.0	100.0	50.0
4.5	90.0	18.0
5.0	80.0	10.0
5.5	75.0	-
6.0	60.0	-
6.5	40.0	-
7.0	30.0	-
7.5	15.0	-
8.0	10.0	-

It took only four days to remove BOD to 10 mg/L at thermophilic temperature but eight days at mesophilic temperature. This shows that high temperature enhances destruction of Biochemical Oxygen Demand (BOD).

Tchobanoglous *et al.* (2004)^[7] stated that oxygen is less soluble in warm water than in cold water. This means that cold water contains more dissolved oxygen than warm water and hence higher biochemical oxygen demand.

a. Total Hydrocarbon Content

Table 2: Total Hydrocarbon Content

Day	Mesophilic (mg/L)	Thermophilic (mg/L)
1	23.53	-
2	15.71	11.16
3	14.25	10.81
4	14.04	10.42
5	12.47	10.00
6	12.37	-
7	10.00	-

It took only four days to remove hydrocarbons to 10 mg/L at

b. Concentration of Solids in the Produced Water

Table 4: Concentration of Solids in the Produced Water

Parameter	Concentration (mg/L) Untreated produced water	Treated Mesophilic (28 °C) (mg/L)	Treated Thermophilic (75 °C) (mg/L)
Volatile Suspended Solids (VSS)	739 (87.35 %)	-	-
Total Suspended Solids(TSS)	28,200.00	30.00	30.00
Total Dissolved Solids (TDS)	4,166.67	1,250.00	710.00

The concentration of solids in the produced water decreased significantly after the treatment. This is an indication of the effectiveness of the treatment process. Volatile suspended solids are better found for viscous liquids e.g. untreated wastewater not for treated wastewater. Sampson (2022)^[6] defined Total Suspended Solids (TSS) as the measured

thermophilic temperature but seven days at mesophilic temperature. This show that thermophilic temperature is more efficient for removal of hydrocarbons.

a. Concentration of Oil and Grease in the Wastewater

Table 3: Concentration of Oil and Grease in the Wastewater

Day	Mesophilic (mg/L)	Thermophilic (mg/L)
1	27.27	26.52
2	24.76	26.304
3	23.50	23.50
4	21.00	15.00
5	15.00	10.00
6	15.00	-
7	14.67	-
8	10.00	-

Table 3 shows that there is a higher concentration of oil and grease at mesophilic temperature than at thermophilic temperature. Treatment at thermophilic temperature was faster as FEPA discharge limit of 10 mg/L was reached in five days compared to eight days for mesophilic treatment.

portion of total solids retained on a 1.58 micrometer glass filter after being dried at 103 °C. Solids in the filtrate that pass through the filter are called Dissolved Solids. Sampson (2022)^[6] defined Volatile Suspended Solids (VSS) as those solids that can be volatilized and burned off when TSS are ignited between 450 °C and 550 °C.

c. Concentration of Heavy Metals that are Present in the Produced Water

Table 5: Concentration of Heavy Metals that are present in the Produced Water

Metal	Untreated produced water (mg/L)	Treated Produced water Mesophilic (28 °C) (mg/L)	Treated Produced water Thermophilic (75 °C) mg/L	FEPA Permissible Discharge Limit (mg/L)
Iron	9.918	3.203	1.195	20.00
Barium	9.500	5.000	3.000	5.00
Manganese	9.000	5.000	4.000	5.00
Selenium	0.001	0.000	0.000	Not specified
Zinc	1.080	0.900	0.800	Less than 1.0
Aluminium	1.150	0.950	0.900	Not Specified
Calcium	5.000	0.980	0.950	200
Copper	0.094	0.091	0.045	Less than 1.0
Magnesium	4.000	0.880	0.850	Not specified
Potassium	7.293	0.100	0.962	Not specified
Sodium	6.598	0.100	0.950	Not specified
Arsenic	0.001	0.000	0.000	0.10
Nickel	9.250	0.095	0.050	Less than 1.0
Cobalt	0.100	0.002	0.001	Not specified
Mercury	0.050	0.010	0.009	0.01
Cadmium	5.000	0.056	0.050	Less than 0.10
Lead	0.090	0.039	0.030	0.05
Chromium	0.025	0.000	0.000	Less than 1.0

Metals that had zero concentration in the untreated wastewater are not listed. The concentration of heavy metals were found to reduce under mesophilic treatment with more

reduction under thermophilic treatment. The results obtained show that treatment at thermophilic temperature could reduce the concentration of heavy metal in the Produced water.

d. Concentration of Polycyclic Aromatic Hydrocarbons present in the Produced Water

Table 6: Concentration of Polycyclic Aromatic Hydrocarbons Present in the Produced Water

Toxicant	Raw produced water (Untreated) (mg/L)	Treated produced water Thermophilic (75 °C) (mg/L)	Treated produced water Mesophilic (28 °C) (mg/L)
Naphthalene	6.76350 E-8	-	-
Acenathathylene	2.58280 E-1	1.47288 E-3	5.18912 E-2
Acenathene	2.75241 E-1	6.18785 E-3	1.07319 E-2
Flourene	5.28321 E-1	5.85383 E-3	4.06487 E-2
Phenanthrene	9.79534 E-1	4.93134 E-3	8.97139 E-2
Anthracene	1.13134 E-1	1.05870 E-3	1.91682 E-2
Flouranthene	5.85390 E-1	7.23035 E-3	5.50877 E-2
Pyrene	1.06411	1.17578 E-2	2.02313 E-1
Benz (a) anthracene	5.64054	1.75000 E-2	3.54764 E-1
Chrysene	2.03512	1.12921 E-1	6.17690 E-1
Benzo (b) flouranthene	3.49985	8.01919 E-1	1.31390
Benzo (k) flouranthene	2.67204	5.42936 E-2	3.68473 E-1
Indeno(1,2,3 – od) Pyrene	1.45034	5.76459 E-2	4.16196 E-1

Table 6 shows that the concentration of polycyclic aromatic hydrocarbons in the wastewater reduced after treatment. The reduction was more for thermophilic treatment at 75 °C than for mesophilic treatment at 28 °C. The most toxic among the polycyclic aromatic hydrocarbons: naphalene, anthracene and phenanthrene were found to be of a lower concentration both in the untreated wastewater and the treated wastewater. According to Owabor & Owihiri (2011) ^[4], naphalene, phenanthrene and anthracene are used as representative of the polycyclic aromatic hydrocarbons as they are in the priority toxicant list of EU and USEPA due to their mutagenic and carcinogenic properties.

e. Negative of the Logarithm of Hydrogen ion Concentration (pH) in the Produced Water

Table 7: Negative of the Logarithm of Hydrogen Ion Concentration (pH) in the Produced Water

Day	Untreated Produced water	Treated produced water Mesophilic (28 °C)	Treated produced water Thermophilic (75 °C)
1	5.8	-	-
5	-	-	6.9
8	-	6.5	-

The untreated produced water had a pH of 5.8. This shows that it is acidic. Treatment of the produced water raised the pH to acceptable level of 6.5 for mesophilic and 6.9 for thermophilic treatment. Federal Environmental Protection

Agency (2002) [2] recommended a pH of 6.5 – 8.5 for treated produced water which is to be discharged into inland water bodies.

a. Impact Analysis of Physico-Chemical Parameters of Thermophilic Anaerobic Digestion Treatment of Produced Water

Table 8: Dispersion Measure of Biochemical Oxygen Demand (BOD) from FEPA Discharge Limit (Assumed Mean) for Thermophilic Anaerobic Digestion Treatment of the Petroleum Wastewater

N	$\left[\frac{BOD}{L}\right]$	Real Mean $\left(\frac{\sum BOD}{N}\right)$	$[BOD - FDL]$ (mg/L)	$[BOD - FEPA Discharge Limit (FDL)]$ (mg/L)	$\left[\frac{\sum(BOD - FDL)}{N}\right]$	$\left[\frac{BOD - FDL}{N}\right]$	$\left[\frac{\sum(BOD - FDL)}{N}\right]$	$\left[\frac{\sum(BOD - FDL)}{N} - \frac{\sum(BOD - FDL)^2}{N}\right]$	$\sqrt{\frac{\sum(BOD - FDL)^2}{N}}$
1	240	100	230	52,900	14,891.42857	28.75	6,241.00	8,650.42857	93.008
2	200		190	36,100		23.75			
3	100		90	8,100		11.25			
4	84		74	5,476		9.25			
5	50		40	1,600		5.00			
6	18		8	64		1.00			
7	10		0	0		0			
Σ	700	100	632	104,240	14,891.42857	79.0	6,241.00	8,650.42857	93.008

$$Coefficient\ of\ Variation = \frac{Standard\ Deviation}{Real\ Mean\ of\ BOD} = \frac{93.008}{100.00} = 0.930 = 93\%$$

coefficient of variation of 0.93 is one among the highest among all the coefficients of variation for all the parameters measured. This show that Biochemical Oxygen Demand (BOD) is one of the most contributing factor to the toxicity of the produced Water and hence one of the most impactful as shown in the impact analysis. A major aspect of the treatment of produced water is therefore the efficiency in the destruction of Biochemical Oxygen Demand.

Multiplying the coefficient by 100 is an optional step to get percentage as opposed to decimal. This is not compulsory. A

Table 9: Dispersion Measure of Total Hydrocarbon Content (THC) from FEPA Discharge Limit (Assumed Mean) for Thermophilic Anaerobic Digestion Treatment of the Produced Water

N	$\left[\frac{THC}{L}\right]$	Real Mean $\left(\frac{\sum THC}{N}\right)$	$[THC - FDL]$ (mg/L)	$[THC - FEPA Discharge Limit (FDL)]$ (mg/L)	$\left[\frac{\sum(THC - FDL)}{N}\right]$	$\left[\frac{THC - FDL}{N}\right]$	$\left[\frac{\sum(THC - FDL)}{N}\right]$	$\left[\frac{\sum(THC - FDL)}{N} - \frac{\sum(THC - FDL)^2}{N}\right]$	$\sqrt{\frac{\sum(THC - FDL)^2}{N}}$
1	23.53	13.184	13.53	183.0609	37.0478	2.706	11.744	25.304	5.03
2	11.16		1.61	1.3456		0.232			
3	10.81		0.81	0.6561		0.405			
4	10.42		0.42	0.17		0.084			
5	10.00		0	0		0			
Σ	65.92	13.184	16.37	185.235	37.0478	3.427	11.744	25.304	5.03

$$Coefficient\ of\ Variation = \frac{Standard\ Deviation}{Real\ Mean\ of\ THC} = \frac{5.03}{13.184} = 0.38 = 38\%$$

Content (THC) in the produced water shows that Total Hydrocarbon Content (THC) is a contributing factor to the pollutant level of the Produced water and therefore should be removed to Nigerian FEPA Discharge Limit before the treated produced water could be discharged into the environment (land and water bodies).

A coefficient of variation of 0.38 for the Total Hydrocarbon

Table 10: Dispersion Measure of Concentration of Oil and Grease (COG) from FEPA Discharge Limit (Assumed Mean) for Thermophilic Anaerobic Digestion Treatment of the Produced Water

N	$\left[\frac{COG}{L}\right]$	Real Mean $\left(\frac{\sum COG}{N}\right)$	$[COG - FDL]$ (mg/L)	$[COG - FEPA Discharge Limit (FDL)]$ (mg/L)	$\left[\frac{\sum(COG - FDL)}{N}\right]$	$\left[\frac{COG - FDL}{N}\right]$	$\left[\frac{\sum COG - FDL}{N}\right]$	$\left[\frac{\sum (COG - FDL)^2}{N}\right]$	$\sqrt{\frac{\sum(COG - FDL)^2}{N}}$
1	27.27	20.415	17.27	298.2529	154.2646632	3.454	108.472	45.793	6.767
2	26.304		16.304	265.820416		3.261			
3	23.50		13.50	182.25		2.70			
4	15.00		05.00	25.00		1.00			
5	10.00		0	0		0			
Σ	102.07	20.415	50.074	771.323	154.2646632	10.415	108.472	45.793	6.767

$$Coefficient\ of\ Variation = \frac{Standard\ Deviation}{Real\ Mean\ of\ COG}$$

$$= \frac{6.767}{20.415} = 0.331 = 33.1\%$$

A coefficient of variation of 0.331 for the Concentration of Oil and Grease (COG) in the produced water show that Concentration of Oil and Grease (COG) is a contributing factor to the pollutant level of the produced water and therefore should be removed to Nigerian FEPA Discharge Limit.

Table 11: Dispersion Measure of the Negative of the Logarithm of Hydrogen ion Concentration (pH) from FEPA Discharge Limit (Assumed Mean) for Thermophilic Anaerobic Digestion Treatment of the Produced Water

N	[pH]	Real Mean of pH	$[pH - FDL]$ (mg/L)	$[pH - FEPA Discharge Limit (FDL)]$ (mg/L)	$\left[\frac{\sum(pH - FDL)^2}{N}\right]$	$\left[\frac{pH - FDL}{N}\right]$	$\left[\frac{\sum pH - FDL}{N}\right]$	$\left[\frac{\sum (pH - FDL)^2}{N}\right]$	$\sqrt{\frac{\sum(pH - FDL)^2}{N}}$
1	5.8	6.35	-1.70	2.89	1.625	-0.85	1.3225	0.3025	0.55
2	6.9		-0.06	0.36		-0.30			
Σ	12.70	6.35	-1.76	3.25	1.625	-1.15	1.3225	0.3025	0.55

$$Coefficient\ of\ Variation = \frac{Standard\ Deviation}{Real\ Mean\ of\ pH}$$

$$= \frac{0.55}{6.35} = 0.087 = 8.7\%$$

A coefficient of variation of 0.087 show that the pH of the produced water should be controlled to be within the Nigerian FEPA Discharge Limit before the treated produced water could be discharged into the environment (land or water bodies).

Table 12: Dispersion Measure of Concentration of Volatile Suspended Solids (VSS) from FEPA Discharge Limit (Assumed Mean) for Thermophilic Anaerobic Digestion Treatment of the produced Water

N	$\left[\frac{VSS}{L}\right]$	Real Mean $\left(\frac{\sum VSS}{N}\right)$	$[VSS - FDL]$ (mg/L)	$[VSS - FEPA Discharge Limit (FDL)]$ (mg/L)	$\left[\frac{\sum(VSS - FDL)^2}{N}\right]$	$\left[\frac{VSS - FDL}{N}\right]$	$\left[\frac{\sum VSS - FDL}{N}\right]$	$\left[\frac{\sum (VSS - FDL)^2}{N}\right]$	$\sqrt{\frac{\sum(VSS - FDL)^2}{N}}$
1	739	739	739	546,121	546,121	739	546,121	0	0
Σ	739	739	739	546,121	546,121	739	546,121	0	0

$$Coefficient\ of\ Variation = \frac{Standard\ Deviation}{Real\ Mean\ of\ VSS}$$

$$= \frac{0}{739} = 0 = 0\%$$

The standard deviation of zero and a coefficient of variation of zero show that Nigerian FEPA should stipulate a discharge

limit for Concentration of Volatile Suspended Solids (VSS) in treated produced water. Nigerian FEPA has no discharge limit for the Concentration of Volatile Suspended Solids (VSS) in treated produced water. The standard deviation of zero and a coefficient of variation of zero does not imply that the Concentration of Volatile Suspended Solids (VSS) does not contribute to the pollutant level of the produced water but that the Nigerian FEPA has not stipulated a discharge limit.

Table 13: Dispersion Measure of Concentration of Total Suspended Solids (TSS) from FEPA Discharge Limit (Assumed Mean) for Thermophilic Anaerobic Digestion Treatment of the Produced Water

N	$\left[\frac{TSS}{L}\right]$	Real Mean $\left(\frac{\sum TSS}{N}\right)$	$TSS - FDL$ (mg/L)	$\left[\frac{TSS - FEPA Discharge Limit (FDL)}{mg/L}\right]^2$	$\left[\frac{\sum(TSS - FDL)^2}{N}\right]$	$\left \frac{TSS - FDL}{N}\right $	$\left[\sum \frac{TSS - FDL}{N}\right]^2$	$\left[\frac{\sum (TSS - FDL)^2}{N}\right]$	$\sqrt{\frac{\sum(TSS - FDL)^2}{N}}$
1	28,200	14,115	28,170	793,548,900	396,774,450	14,085	198,387,225	198,387,225	14,085
2	30		0	0					
Σ	28,230	14,115	28,170	793,548,900	396,774,450	14,085	198,387,225	198,387,225	14,085

$$Coefficient\ of\ Variation = \frac{Standard\ Deviation}{Real\ Mean\ of\ TSS}$$

$$= \frac{14,085}{14,115} = 0.998 = 99.8\%$$

A coefficient of variation of 0.998 ranks Concentration of

Total Suspended Solids (TSS) in the produced water as the highest potential hazard in the produced water, which contributes to the toxicity of the produced water. Therefore, Total Suspended Solids (TSS) should be removed to Nigerian FEPA Discharge Limit before the treated produced water could be discharged into the environment (land or water bodies).

Table 14: Dispersion Measure of Concentration of Total Dissolved Solids (TDS) from FEPA Discharge Limit (Assumed Mean) for Thermophilic Anaerobic Digestion Treatment of the Produced Water

N	$\left[\frac{TDS}{L}\right]$	Real Mean $\left(\frac{\sum TDS}{N}\right)$	$TDS - FDL$ (mg/L)	$\left[\frac{TDS - FEPA Discharge Limit (FDL)}{mg/L}\right]^2$	$\left[\frac{\sum(TDS - FDL)^2}{N}\right]$	$\left \frac{TDS - FDL}{N}\right $	$\left[\sum \frac{TDS - FDL}{N}\right]^2$	$\left[\frac{\sum (TDS - FDL)^2}{N}\right]$	$\sqrt{\frac{\sum(TDS - FDL)^2}{N}}$
1	4,166.67	2,438.335	2,166.67	4,694,458.889	3,179,279.445	1083.335	192,137.5722	2,987,141.873	1,728.335
2	710.00		-1,290	1,664,100		-645			
Σ	4,876.67	2,438.335		6,358,558.889	3,179,279.445	438.335	192,137.5722	2,987,141.873	1,728.335

$$Coefficient\ of\ Variation = \frac{Standard\ Deviation}{Real\ Mean\ of\ TSS}$$

$$= \frac{1,728.335}{2,438.335} = 0.709 = 70.9\%$$

A coefficient of variation of 0.709 shows that Concentration of Total Dissolved Solids (TDS) is a potential pollutant in the produced Water next to Biochemical Oxygen Demand (BOD) and Total Suspended Solids (TSS).

A coefficient of variation that is greater than 1.0 indicates that error is greater than the treatment. Coefficient of variation shows how far the observation is from the true value which in this case is the Nigerian Federal Environmental Protection Agency (FEPA) discharge limits. The higher the coefficient of variation, the further away the parameter is from the FEPA discharge limit and hence the higher the contribution of the parameter to the pollutant level of the produced water. From the impact analysis carried out, the concentration of Total Suspended Solids (TSS) is the highest contributor to the pollutant level of the produced water and hence produced water must be treated so as to remove the Total Suspended Solids (TSS) to the FEPA discharge limit either by filtration or by adsorption. Biochemical Oxygen Demand (BOD), the demand for oxygen required for decomposition of organic matter is the next highest contributor to the pollutant level of the produced water hence produced water must be treated so as to destroy the Biochemical Oxygen Demand so as to make more oxygen available for life in the aquatic environment. The coefficient of variation for the concentration of Volatile Suspended Solids (VSS) in the produced water is zero because the Nigerian FEPA did not stipulate a discharge limit for concentration of Volatile Suspended Solids (VSS).

Table 15: Coefficient of Variation for Physico – chemical Parameters of Thermophilic Anaerobic Digestion Treatment of the Produced Water

Parameters	Coefficient of Variation
Concentration of Total Suspended Solids (TSS)	0.998
Biochemical Oxygen Demand (BOD)	0.93
Concentration of Total Dissolved Solids (TDS)	0.709
Total Hydrocarbon Content (THC)	0.38
Concentration of Oil and Grease (COG)	0.331
pH	0.087
Concentration of Volatile Suspended Solids (VSS)	0

a. Nigerian Federal Environmental Protection Agency Discharge Limits (One of the Design Basis)

Table 16: Raw Values and Final Values of Physico-chemical Parameters of the Produced Water

Parameter	Raw Value	Final Value	FEPA Discharge Limits	Remarks
Biochemical Oxygen Demand	2,784.0 mg/L	10.0 mg/L	10.0 mg/L	Thermophilic anaerobic digestion of the produced water destroyed the Biochemical Oxygen Demand (BOD) thus making more oxygen available for life in the aquatic environment.
Total Hydrocarbon Content	23.53 mg/L	10.0 mg/L	10.0 mg/L	Thermophilic anaerobic digestion of the produced water removed hydrocarbons which makes the water toxic to aquatic life and carcinogenic to man to an acceptable limit.
Concentration of Oil and Grease	27.27 mg/L	10.0 mg/L	10 mg/L	Oil and Grease which blocks oxygen transfer, interferes with reaction and produces aesthetically poor appearance in the water was removed to acceptable limit.
Volatile Suspended Solids	739 mg/L	10 mg/L	NIL	Nigerian Federal Environmental Protection Agency (FEPA) does not have discharge limit for Volatile Suspended Solids (VSS).
Total Suspended Solids	28,200 mg/L	30.0 mg/L	30.00 mg/L	The concentration of Total Suspended Solid (TSS) which causes deterioration of water quality was reduced to an acceptable limit
Total Dissolved Solids	4,166.67 mg/L	710.0 mg/L	2000.0 mg/L	The concentration of Total Dissolved Solid (TDS) which impairs industrial and domestic uses of water by causing hardness of the water is reduced to acceptable limit.
pH	5.8	6.9	6.5-8.5	Thermophilic anaerobic digestion reduced the acidity level of the produced water making it harmless for life in the aquatic environment

FEPA discharge Limits taken from: Federal Environmental Protection Agency (2002) ^[2]

The produced water was treated to Nigerian Federal Environmental Protection Agency (FEPA) discharge limits. These discharge limits constitute the basis for the experiments conducted. The produced water must be treated to FEPA discharge limit before being discharged into water bodies.

Table 17: Percentages of Pollutants removed in Thermophilic Anaerobic Digestion Treatment of the Produced Water

Pollutant	Percent Removed
Oil and Grease	63.33
Suspended Solids	99.89
Hydrocarbons	70.85
Dissolved Solids	82.96
Organic Matter	99.96
Heavy Metals	95.65
Nitrogen	99.99
Phosphorus	58.33

The percentages of pollutants removed indicates high efficiency in removal of pollutants from the produced water and hence high efficiency in the treatment of the produced water.

% Error is approximately 0 % for all the pollutants in the produced water. This shows removal efficiency was approximately 100%.

4. Conclusion and Recommendations

4.1. Conclusion

An impact analysis of pollutants in produced water was carried out. From the impact analysis, the concentration of Total Suspended Solids (TSS) in the produced water was found to be the most potential among the pollutants in the produced water for having a coefficient of variation of 0.998 equivalent to 99.8 %. A coefficient of variation of 0.998 indicates that the treatment is greater than the error as it is less than 1.0 or 100 %. A coefficient of variation of 0.998 shows that the concentration of Total Suspended Solids in the produced water is the furthest away from FEPA discharge limit and hence the highest contributor to the pollutant level of the produced water.

4.2. Recommendation

It is recommended that

Produced water should be treated so as to remove the Total Suspended Solids (TSS) to the FEPA discharge limit either by filtration or by adsorption

Produced water should be treated so as to make more oxygen available for life in the aquatic environment. Besides this, produced water must be treated to remove the concentration of Total Dissolved Solids (TDS), the Total Hydrocarbon Content (THC), the Concentration of Oil and Grease (COG), the negative of the logarithm of hydrogen ion concentration (pH), etc. to FEPA discharge limits so as to safeguard the environment and ecosystem.

Nigerian FEPA should stipulate a discharge limit for concentration of Volatile Suspended Solids (VSS) in produced water as Volatile Suspended Solids and Volatile

organic compounds also contribute to the pollutant level of produced water as seen in literature.

Appendix A

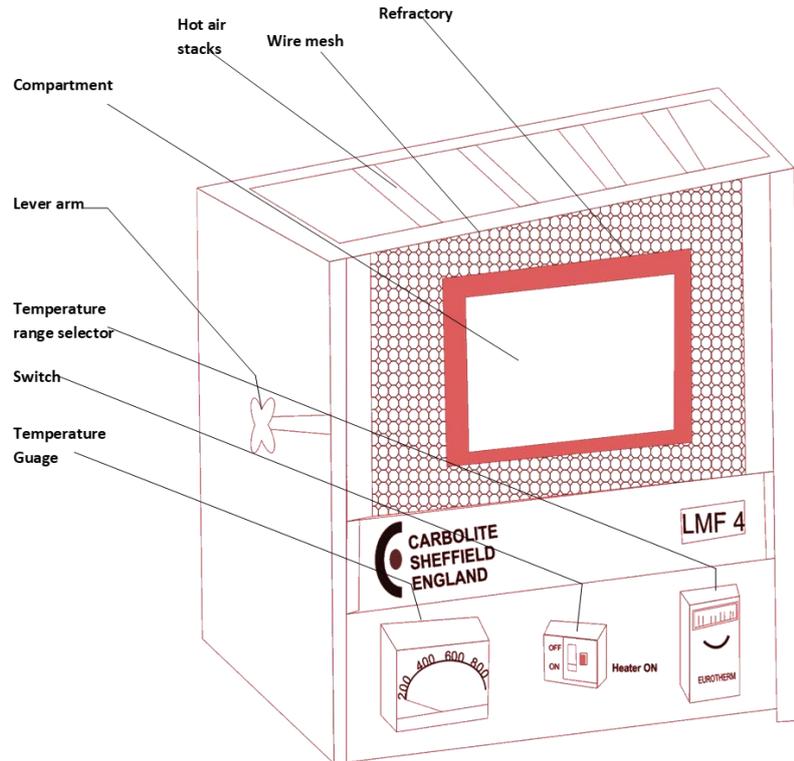


Fig 2: Muffle Furnace LMF4

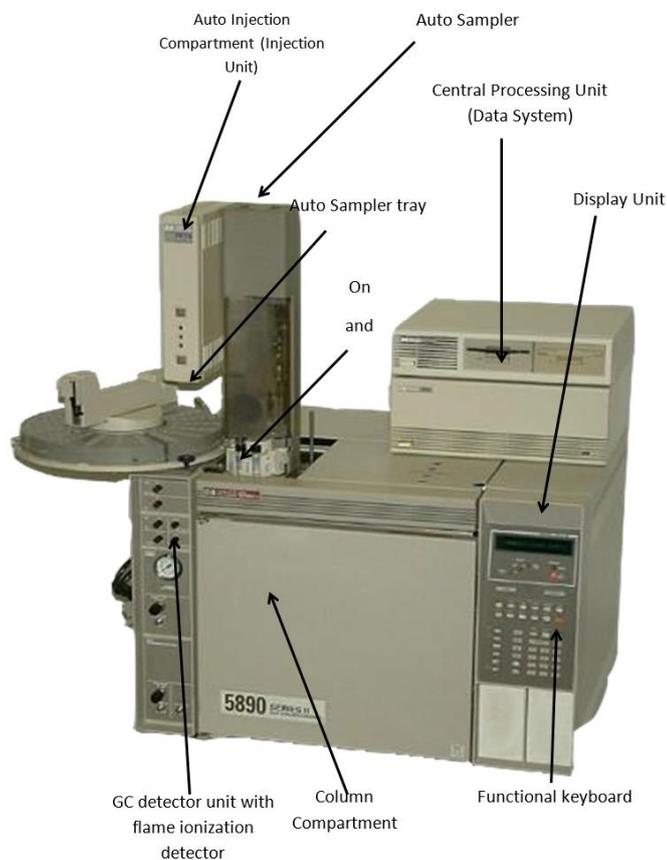


Plate 1: Hewlett Packard (HP) 5890 Series II GC with FID

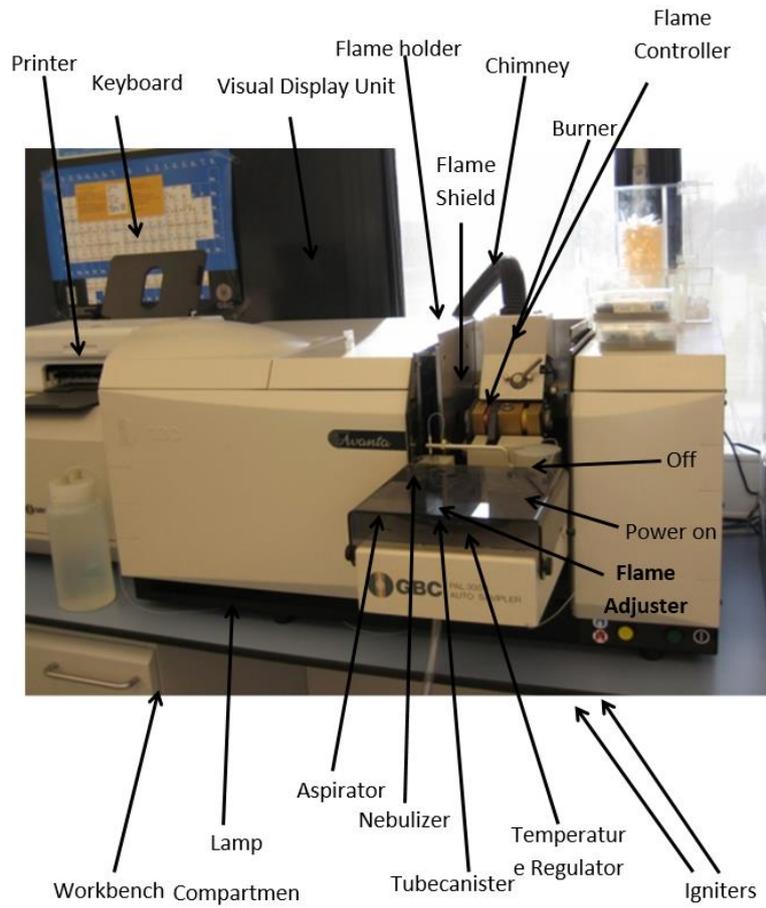


Plate 2: GBC Avanta Atomic Absorption Spectrophotometer



Plate 3: Jenway 6305 Uv/Visible Spectrophotometer



Plate 4: Anaerobic Jar with Wastewater in Anaerobic Incubator Maintained At 75°C



Plate 5: Anaerobic Jar with Culture Plates in an Incubator maintained at 75 °C

**Appendix B
Graphs and Waveforms**

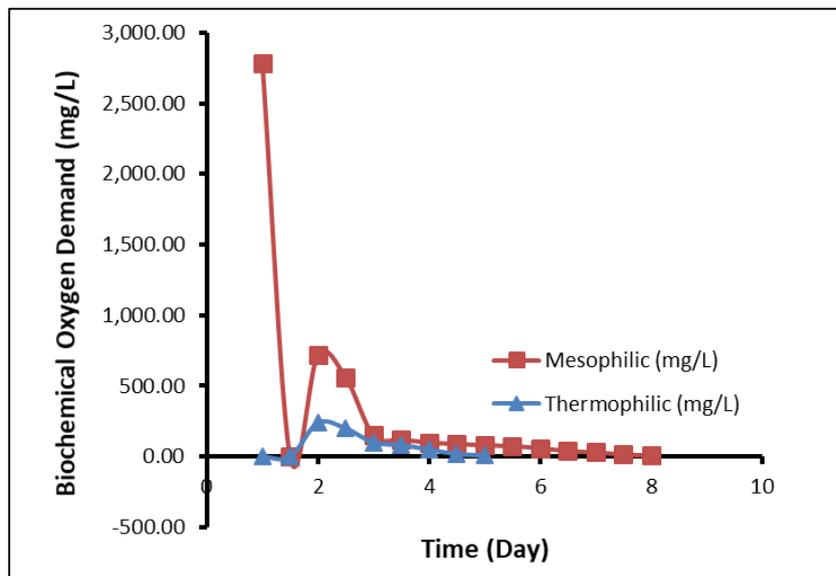


Fig 3: Change in Biochemical Oxygen Demand with Time

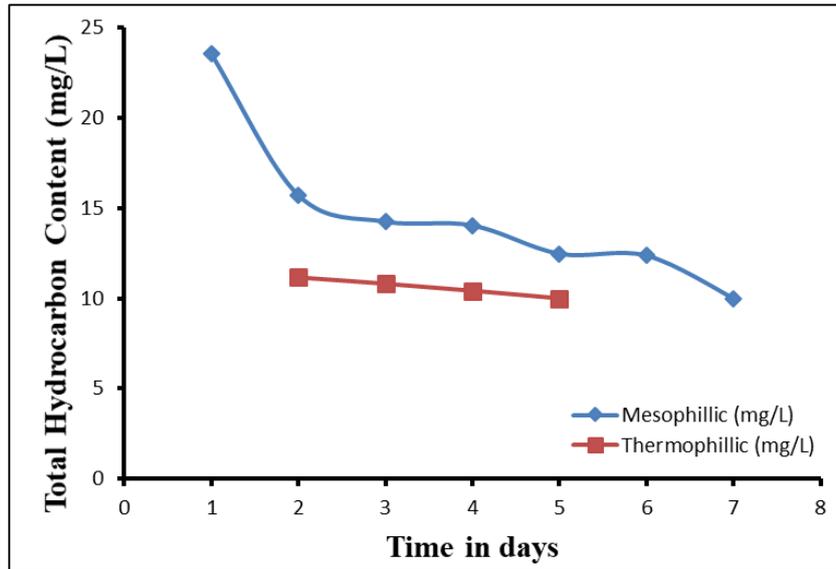


Fig 4: Change in Total Hydrocarbon Content with Time

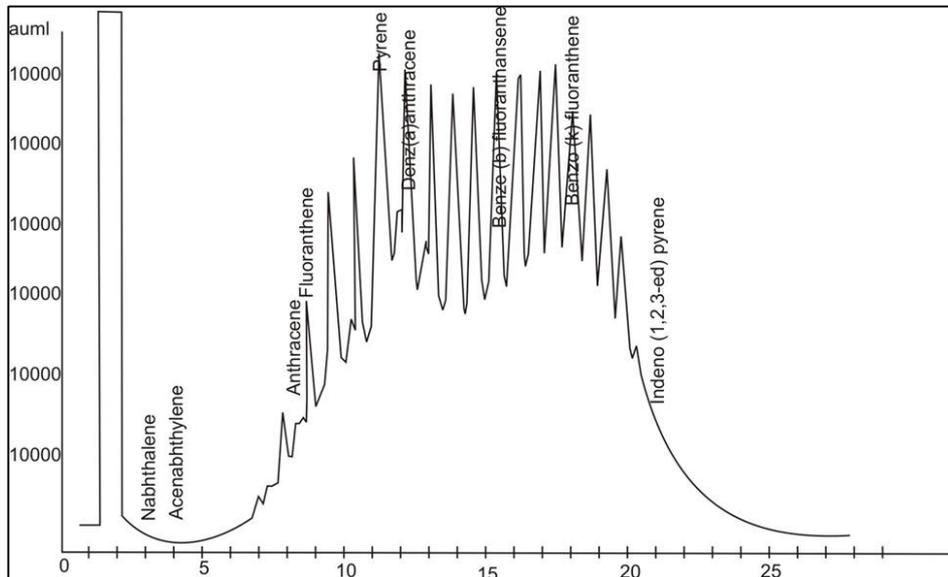


Fig 5: Waveform for GC Analysis of Polycyclic Aromatic Hydrocarbons in Untreated Produced Water

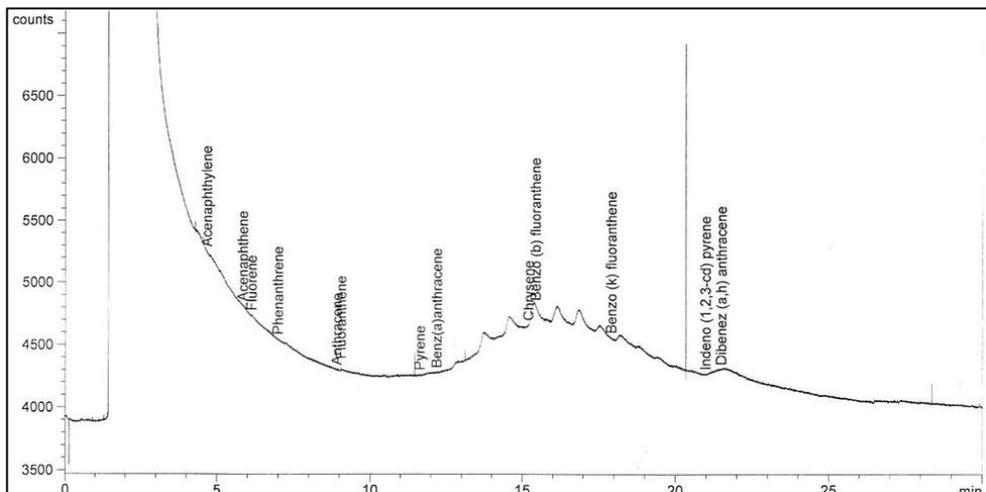


Fig 6: Waveform for GC analysis of Polycyclic Aromatic Hydrocarbons in the Produced Water Treated at 75 °C (Thermophilic)

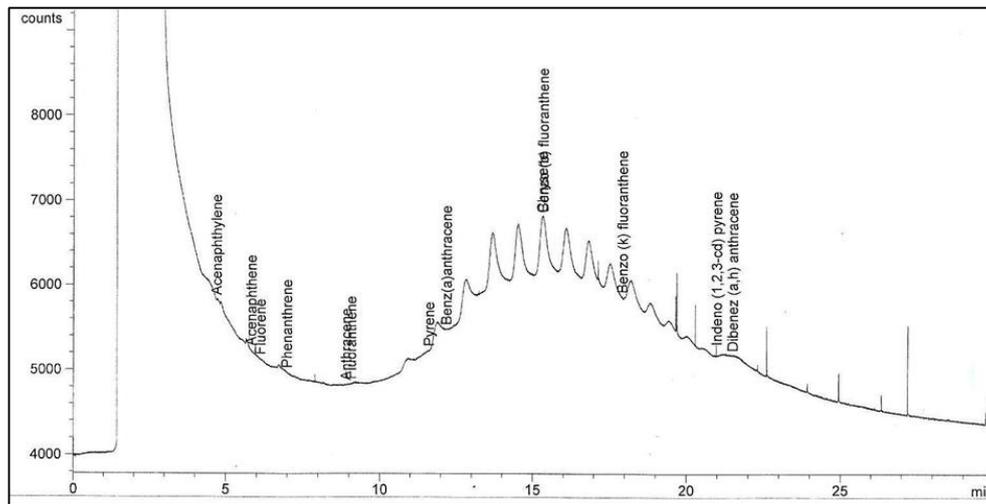


Fig 7: Waveform for GC analysis of Polycyclic Aromatic Hydrocarbons in the Produced Water Treated at 37 °C (Mesophilic)

5. References

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