OPTIMISATION OF ANAEROBIC DIGESTION TREATMENT OF PETROLEUM SLUDGE

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ABSTRACT
Anaerobic digestion treatment of petroleum sludge increases Nigerian gross domestic product and enhance sustainable development as it yields biogas and biosolids fertilizer. The potential of anaerobic digestion for the treatment of Petroleum sludge was proved by a reduction in Biochemical Carbonaceous Oxygen Demand (BCOD) of the sludge from 6080 mg/L to 20.40 mg/L and Total Hydrocarbon Content (THC) from 57000 ppm to 1500 ppm. Gas Chromatography and Mass Spectrothermotometry (GC-MS) result showed a decrease in concentration of Polycyclic Aromatic Hydrocarbons (PAHs) from 37.1 mg/L to 0.32 mg/L Naphthalene; 33.43 mg/L to 8.24 mg/L Anthracene and 33.97 mg/L to 9.86 mg/L Phenanthrene. Anaerobic digestion of 200 grammes of the sludge gave 10,500 m³/d biogas and 190 g biosolids with NPK value of 5.0 mg/kg Nitrate, 30.0 mg/kg Phosphate and 695.95 mg/kg Potassium. For 5 Tons per day of sludge plant capacity, economic analysis gave 2 years Pay Back Period (PBP) and 47 % Rate of Return on Investment (ROI). This show that a petroleum sludge anaerobic digestion plant if well managed could be economically viable in Nigeria. The plant should be located as a process unit in every Nigerian process industry, waste water treatment plant and sites where sludges are dumped.

Keywords: Polycyclic Aromatic Hydrocarbons; Biochemical Carbonaceous Oxygen Demand; Total Hydrocarbon Content; Spectrothermotometry; Economic Viability.

1.0. INTRODUCTION
The disposal of untreated petroleum sludge causes environmental and health hazards because of disease pathogens present in the untreated sludge. The treatment of sludge destroys the disease pathogens to enable an industry meet Environmental Protection Agency standards and regulations for treatment and disposal of sludge. Besides health related problems, disposal of untreated petroleum sludge onto land or water bodies causes land pollution, water pollution and destruction of ecosystem. Moreover, the treatment of sludge in anaerobic digesters yields the environmentally friendly and renewable energy source, biogas a substitute for natural gas and biosolids, a substitute for petrochemical based fertilizers. In Nigeria, the treatment and disposal of sludge in accordance with EPA specifications imposes a major challenge to the oil and gas industry. Winter (1984) states that anaerobic biogas digesters have historically been used for sewage sludge stabilization in Waste Water Treatment Plants (WWTPs). Owabor and Owihiri (2011) give the priority pollutants as the Polycyclic Aromatic Hydrocarbons (PAHs) which are known to be in the priority list of EU and EPA due to their mutagenic and carcinogenic properties to be naphthalene, phenanthrene and anthracene which can be used as representative of the PAHs.

Besides destroying disease pathogens in the sludge, anaerobic digestion treatment of sludge yields biogas and biosolids fertilizer hence saving the fuel needed to manufacture petrochemical based fertilizers (Appels et al., 2008). Moreover, besides being cheaper, biosolids fertilizer is retained in the soil longer than petrochemical based fertilizers as it does not easily get leached. Biogas produced from anaerobic digestion is useful for generating power for operating the plant, hence optimizing operational cost of the plant (Appels et al., 2008). Although Nigerian natural gas reserve is exponentially increasing, biogas is more advantageous being a renewable energy source and more environmentally friendly as it produces less greenhouse emissions as it has less carbon. Moreover, adequate treatment prevents corrosion to user equipments. It is emphasized in Hakan et al. (2009) that other renewable energy sources lay claim to large areas of arable land thereby hampering food production. This technical paper describes anaerobic digestion Process for petroleum
Optimisation of Anaerobic Digestion Treatment of Petroleum Sludge

sludge treatment and its numerous economic advantages. Moreover, mathematical modeling, process optimization and troubleshooting of the anaerobic digestion plant are also included in the paper.

1.1. Process Description

1.1.1. Microbial Digestion

The thickened sludge was pretreated to disrupt chemical bonds of cell walls and membranes thus enhancing solubilisation of cell components. The sludge was degraded in anaerobic digester by microbial action in the absence of oxygen to biogas and NPK rich bio solids fertilizer. The supernatant from the digester and water from the thickener were recycled to the Waste Water Treatment Plant (WWTP) and the bio solids dried, pelletised and sent to bagging unit. Green and Perry (1997) gave Solid Retention Time (SRT) of 15 – 30 days, Hydraulic Retention Time (HRT) of 10 – 30 days, Temperature 30 – 38 °C, Mesophillic and 50 – 70 °C, Thermophillic. Boe (2006) give optimum pH for the methanogenic bacteria to be between 6.5 to 7.2.

1.1.2. Formation of Biogas

The formation of biogas from anaerobic digestion of petroleum sludge involve four basic steps (Appels et al., 2008): Hydrolysis, acidogenesis, acetogenesis and methanogenesis. Among these, hydrolysis is the rate limiting step. These steps are illustrated on Figure 1.

1.1.3. Biogas Up gradation

Impurities in the biogas are removed by Pressure Swing Adsorption (PSA) on activated carbon. Since adsorption takes place at high temperature and pressure, desorption is achieved by depressurizing. Moisture is removed from the biogas by drying. The active site of the adsorbent retains water vapour and other pollutants thus decreasing adsorbent life hence desorption is frequently carried out by depressurizing. Moreover, siloxanes are difficult to desorb from the adsorbent beds, so the adsorbent beds should be replaced regularly e.g weekly. The biogas is dried, compressed and sent to storage.

Petroleum Sludge

Hydrolysis

Soluble Organics

Acidogenesis (acidogens)

Volatile Fatty Acids (VFA)

Acetogenesis (acetogens)

H₂, CO₂

CH₄ + CO₂ (Biogas)

Methanogenesis (methanogens)

Methanogenesis (methanogens)

Figure 1: Steps in Anaerobic Digestion Process of Petroleum Sludge (Source: Appels et al. (2008))
Figure 2: Block Flow for Anaerobic Digestion Process

Figure 3: Process Flow for a typical Anaerobic Digestion Process
1.1.4. Kinetic Models

Applying the Monods Kinetics for continuous stirred mode with substrate inhibition, the following Kinetic Models were obtained for the biomass and for the sludge.

From material balance equation:

Flow of materials In + Microbial Biodegradability of Sludge - Flow of Materials OUT = Accumulation (1)

For the Biomass

\[ Fx_{1,0} + \mu x_1 V - Fx_1 = \frac{Vdx_1}{dt} \] (2)

Dividing through by \( V \)

\[ \frac{dx_1}{dt} = \frac{F}{V} (X_{1,0} - X_1) + \mu x_1 \] (3)

From Monods equation: \( \mu = \frac{\mu_m x_2}{k_m + x_2} \), we have

\[ \frac{dx_1}{dt} = D(X_{1,0} - X_1) + \frac{\mu_m x_1 x_2}{k_m + x_2} - k_d x_1 \] (4)

Writing in the pattern of the modified form of monods equation: \( \mu = \frac{\mu_m x_2}{k_m + x_2} - k_d \) to account for consumption of cellular material to produce maintenance energy.

\[ \frac{dx_1}{dt} = D(X_{1,0} - X_1) + \frac{\mu_m x_1 x_2}{k_m + x_2} - k_d x_1 \] (5)

For the Sludge

From materials balance:

Flow of materials In + Microbial Biodegradability of Sludge - Flow of Materials OUT = Accumulation

\[ Vdx_2 \frac{dt}{dt} = FX_{2,0} - \frac{\mu x_1 V}{Y} - FX_2 \] (6)

\[ \frac{Vdx_2}{dt} = F(X_{2,0} - X_2) - \frac{\mu x_1 V}{Y} \] (7)

Dividing through by \( V \)

\[ \frac{dx_2}{dt} = D(X_{2,0} - X_2) - \frac{\mu x_2}{Y} \] (8)

From Monods equation: \( \mu = \frac{\mu_m x_2}{k_m + x_2} \)

\[ \frac{dx_2}{dt} = D(X_{2,0} - X_2) - \frac{\mu_m x_1 x_2}{Y(k_m + x_2)} \] (9)

Where: \( X_1 \), is the concentration of Biomass (mg/L)

\( X_2 \), the concentration of Sludge (mg/L)

\( X_{1,0} \), initial concentration of Biomass (mg/L)

\( X_{2,0} \), initial concentration of Sludge (mg/L)

\( F \), Volumetric flow rate of feed (m³/s⁻¹)

\( V \), Volume of reactor used (m³)

\( D \), Dilution rate or space velocity (hr⁻¹)

\( \mu \), Specific growth rate (hr⁻¹)

\( \mu_m \), Maximum specific growth rate or half minimal velocity concentration (hr⁻¹)

\( K_m \), Monods constant (kmol/m³)

\( K_d \), Coefficient of endogenous respiration or specific maintenance rate (d⁻¹)

\( Y \), Yield coefficient (mgVSS/mgBCOD)

\( VSS \), Volatile Suspended Solids

\( BCOD \), Biochemical Carbonaceous Oxygen Demand

1.1.5 Troubleshooting

Troubleshooting of anaerobic digester plant is in exhaustive. Readers are therefore referred to the operations manual by Zickefoose and Hayes (1976) (www.nepis.epa.gov)

1.1.6. Optimisation

The optimization of anaerobic digestion and the assessment of its operation as a function of varying feed or operating conditions can be achieved using appropriate digestion models provided in AQUASIM software to:

i. Estimate the optimum retention time, reactor volume, gas production and composition for a requested system performance and investigate the sensitivity of the system performance to various parameters.

ii. Predict on a time basis how the system will react to sudden or progressive changes in operating parameters of feedstock flow rate and composition, temperature, inhibition, pH, Etc and choose the optimum conditions.

2.0. MATERIALS AND METHODS

2.1. Materials

Petroleum sludge was collected from Akpada flow station, Shell Petroleum Development Company, Port Harcourt, Nigeria. Methanogenic bacteria (Methanobrevibacter) was isolated from the intestine of a cow and stored in glycerine. Oxoid Anaero Gen TM AN 0035A gas park was used in anaerobic Jar to create anaerobic condition.

2.2. Methods

2.2.1. Pretreatment of Petroleum Sludge

Petroleum sludge was heated on a hot plate and dried in an oven to remove water after which it was crushed. This helped break the cell walls and membranes.

2.2.2. Total Anaerobic Bacterial Count

To perform the each day tenfold serial dilution, the medium (nutrient agar) was prepared as directed by the manufacturers of nutrient agar (LAB M) and all the
glassware, media and diluents such as physiological Saline were sterilized using autoclave.

After performing the tenfold serial dilution, 0.1ml of the desired dilution was transferred to the sterile dry agar plate and spread with a sterile hockey bent glass rod. The inoculation was performed in duplicate plates of any of the desired diluents. The culture plates were all incubated at 37 °C for 24 hours using a Labtech anaerobic jar fitted with Gas Park and catalyst for anaerobic incubation. Once incubation was over, the plates average were counted in duplicates and average counts were calculated and further used for calculation of the colony forming units per gram (cfu/g) of the sample using the formula in equation (10). Where DF is the Dilution factor.

\[
TABC = \frac{1}{\text{DF}} \times \frac{\text{Average of plate bacteria count}}{\text{Volume Correction factor}}
\]

(10)

The bacterial count was carried out each day and a new gas park replaced each day.

2.2.3. Measurement of Biochemical Carbonaceous Oxygen Demand

0.1g sludge was weighed into a clean beaker and 200 ml of mineral water from the reagent dissolved oxygen bottle introduced into the sludge. This was stirred to disperse the sludge and obtain a homogenous mixture. The mixture was re-introduced into two dissolved oxygen reagent bottles filled to the brink 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 mls 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 sludge 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 BCOD value was calculated using equation (11)

\[
BCOD = \frac{DD_{\text{initial}} - DD_{\text{final}}}{\text{Dilution Factor}}
\]

(11)

2.2.4. Measurement of Volatile Suspended Solids

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 (12)

\[
\% \text{Volatile Suspended solids} = \frac{\text{Weight of Volatile residue}}{\text{Weight of residue}} \times 100
\]

(12)

2.2.5. Measurement of Total Hydrocarbon Content

0.01 gramme of sludge was weighed into a clean beaker and was diluted to 100 ml volume with chloroform and put into the sample compartment of the thermospectronic spectrophotometer. The absorbance was read at 420 nm wavelength using chloroform as blank. The absorbance obtained was recorded. The concentration of hydrocarbon in the sludge was calculated using the formular in equation (13)

\[
\text{THC} = \frac{\text{Absorbance of sludge} \times \text{Gradient of standard graph}}{\text{weight of sample diluted in 100ml} \times \frac{1}{\text{Dilution Factor}}}
\]

(13)

2.2.6. Measurement of Concentration of Polycyclic Aromatic Hydrocarbons

The sludge or biosolids sample was extracted according to USEPA 3550 C using the ultrasonic extraction method. 10 g of the sample was extracted with dichloromethane. The extract was concentrated and 1ml of the sample extract was injected and analyzed using Agilent 7890 GC-MS according to USEPA 8270.

Five different calibration stocks were prepared in dichloromethane according to manufacturers Standard and peaks of size of different standards prepared used to plot a graph. The concentration of the analyzed sample was extrapolated from the graph of the standard sample.
2.2.7. Measurement of Fertilizer Value of Biosolids

2.2.7.1. Measurement of Phosphate (Phosphorus) Content in Biosolids

1 gramme of biosolids sample was extracted with 50 ml, 2.5 % glacial acetic acid. The extract was filtered into 250 ml capacity conical flask and 0.8 ml of combined reagent was added to the flask. A blank and standard phosphate ion concentration ranging from 0.001 - 0.007 was prepared and 0.8 ml combined reagent added respectively.

The bluish colour developed within 30 mins interval was read at 840 nm wavelength in thermospectronic spectrophotometer. Absorbance of the sample extracted was also read at the same wavelength and recorded. The concentration of the phosphate ion in the sample was calculated using equation (14).

\[
\text{Concentration of ion} = \text{Concentration of sample extrapolated from concentration versus absorbance graph in mg/l} \times \text{Conversion factor to mg/kg} \quad (14)
\]

2.2.7.2. Measurement of Nitrate Content of Biosolids

0.5 ml Brucin reagent was added to 1mg of the biosolids sample in a beaker. 2 ml of concentrated sulphuric acid was then added and 1 ml of the mixture pipetted into a clean test tube. The yellowish colour formed was read at 400nm in a Thermospectronic Spectrophotometer. The concentration of nitrate in the biosolid sample was calculated using equation (14).

2.2.7.3. Measurement of Potassium ion Concentration in Biosolids

The biosolids sample was diluted and made up to 50 mls with distilled water. 766 nm wavelength was selected. Slit width, air and gas pressure was adjusted and settings programmed. Standard potassium ion concentrations were aspirated into the instrument “Bunsen Chamber” to calibrate the equipment and to plot a graph of standard ion. The aspirator tubing system was occasionally flushed with water before samples were aspirated. The absorbance and concentration of potassium ion in the sample was automatically displayed on the equipment screen and also printed out for documentation. The concentration of potassium ion in the biosolids was calculated using equation (14).

2.2.8. Detection of Biogas

After collecting some of the gas in a balloon, the gas evolved from the anaerobic jar was made to pass through a small metallic hose connected to a Bunsen burner. Methane gas was confirmed by the blue colour of the flame. The flow gauge at the gas collection point read 0.122 m$^3$s$^{-1}$. This was found to be equivalent to 10,500 m$^3$/d

3.0. RESULTS

3.1. Total Anaerobic Bacterial Count (TABC)

<table>
<thead>
<tr>
<th>Day</th>
<th>Anaerobic Bacterial Count $cfu/g \times 10^9$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.129</td>
</tr>
<tr>
<td>2</td>
<td>1.020</td>
</tr>
<tr>
<td>3</td>
<td>1.021</td>
</tr>
<tr>
<td>4</td>
<td>2020</td>
</tr>
<tr>
<td>5</td>
<td>2020</td>
</tr>
<tr>
<td>6</td>
<td>2019</td>
</tr>
<tr>
<td>7</td>
<td>2018</td>
</tr>
<tr>
<td>8</td>
<td>2017</td>
</tr>
<tr>
<td>9</td>
<td>2016</td>
</tr>
<tr>
<td>10</td>
<td>2015</td>
</tr>
<tr>
<td>11</td>
<td>8010</td>
</tr>
<tr>
<td>12</td>
<td>87</td>
</tr>
<tr>
<td>13</td>
<td>8.50</td>
</tr>
<tr>
<td>14</td>
<td>8.45</td>
</tr>
<tr>
<td>15</td>
<td>7.20</td>
</tr>
<tr>
<td>16</td>
<td>7.199</td>
</tr>
</tbody>
</table>
3.2. Biochemical Carbonaceous Oxygen Demand and Total Hydrocarbon Content

Table 2: Biochemical Carbonaceous Oxygen Demand and Total Hydrocarbon Content

<table>
<thead>
<tr>
<th>DAYS</th>
<th>BCOD (mg/L)</th>
<th>THC (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6080</td>
<td>57000</td>
</tr>
<tr>
<td>4</td>
<td>1200</td>
<td>30,000</td>
</tr>
<tr>
<td>16</td>
<td>20.40</td>
<td>1500</td>
</tr>
</tbody>
</table>

Fig. 4: Bacterial growth rate per day

Fig. 5: Graph of change in BCOD with Time (days)
3.3. Polycyclic Aromatic Hydrocarbons (PAHs)

GC-MS Waveforms
Table 3: GC – MS for the priority Toxicants in the Petroleum Sludge

<table>
<thead>
<tr>
<th>Toxicant</th>
<th>Concentration (mg/L)</th>
<th>Untreated Sludge</th>
<th>Biosolids</th>
</tr>
</thead>
<tbody>
<tr>
<td>Napthalene</td>
<td>37.1</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td>Anthracene</td>
<td>33.43</td>
<td>8.24</td>
<td></td>
</tr>
<tr>
<td>Phenanthrene</td>
<td>33.97</td>
<td>9.86</td>
<td></td>
</tr>
</tbody>
</table>

3.4. Fertilizer Value of Bio solids

Table 4: Fertilizer Value of Bio solids

<table>
<thead>
<tr>
<th>Component</th>
<th>Absorbance</th>
<th>Concentration mg/L</th>
<th>Conversion Factor</th>
<th>Concentration mg/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrate</td>
<td>0.01</td>
<td>0.1</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>Phosphate</td>
<td>0.6</td>
<td>0.6</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>Potassium</td>
<td>1.3384</td>
<td>13.919</td>
<td>50</td>
<td>695.95</td>
</tr>
</tbody>
</table>

3.5. Volume of Biogas Produced

\[ V_{CH_4} = (0.35)(s_o - s)(Q)(10^3 g/kg)^{-1} - 1.42P_x \]

\[ (Tchobanoglous et al., 2004) \]

\[ P_x = \frac{Y_{ESO}}{1+k_d \theta_c} \]

\[ (Appels et al., 2008) \]

\[ Y = \frac{mg_{VSS}}{mg_{BCOD}} \]

\[ = \frac{99.6}{6080} = 0.016 \]

From equation (16)

\[ P_x = \frac{0.016 \times 0.9 \times 6080}{1 + 0.025 \times 16} = \frac{87.552}{1.40} = 62.54 \, kg/d \]

**Volume of Methane**

From equation (15)

\[ V_{CH_4} = (0.35)(S_o - S)(Q)(10^3 g/kg)^{-1} - 1.42P_x \]

\[ (0.35)(6080 - 20.4) \times \frac{1}{1000} - 1.42(62.54) \]

\[ = 0.35(6059.6)(5) - 88.8068 \]

\[ = 10,603.25 - 88.8068 \]

\[ = 10,514.4432 \, m^3/d \]

\[ \approx 10,500 \, m^3/d \, biogas \, for \, 16 \, days. \]

3.6. Economic Evaluation

Net Annual Profit (NAP) = [ Product Sales ] – [ Operating Cost + Fixed Capital] (18)
Total Investment (TI) = Fixed capital + Working capital

Calculations for Net Annual Profit, Total Investment, Etc could be obtained from appendix 1 of Sampson (2018).

Rate of Return on Investment (ROI) = \[
\frac{\text{Net annual profit}}{\text{Total investment}} \times 100
\]

\[
= \frac{\£4,937,767.42}{\£10,452,170.28} \times 100 = 47.2415516 \approx 47\%
\]

Pay Back Period = \[
PBP = \frac{\text{Total investment}}{\text{Net annual profit}}
\]

\[
= \frac{\£10,452,170.28}{\£4,937,767.42} = 2.1167806 \approx 2 \text{ years}
\]

OR:

\[
\frac{1}{\text{Rate of return on investment}} = \frac{1}{47}\%
\]

\[
= 2.127659576 \approx 2 \text{ years}
\]

4.0. DISCUSSION

Recycle on day 4 resulted in exponential increase in micro-organisms. From Table 1 and Fig. 4 the Microbial digestion was terminated after sixteen days at the falling rate phase when most of the micro-organisms must have died. Table 2 and Figs 5 & 6 show that BCOD and THC decreases with sludge biodegradation. BCOD and THC can therefore be used as a measure of sludge biodegradation. Figures 7 and 8 show that concentration of Polycyclic Aromatic Hydrocarbons (PAHs) are higher in the untreated sludge and negligible in the biosolids produced.

The potential of anaerobic digestion for the treatment of sludge is proved by GC-MS analysis for priority toxicants in the sludge. Table 3 show that the concentration of Naphthalene, Anthracene and phenanthrene in the untreated sludge reduced from tens to units after the sludge treatment. Table 4 show that the treated sludge referred to as biosolids can be used as fertilizer as it is rich in Nitrate, Phosphate and Potassium. The gaseous effluent (biogas) can be obtained in substantial amount from anaerobic digestion of the sludge as shown in the analysis of equation (15). The time of conversion. It is worthy of note that the values of the rate of return on investment and payback period are not dependent on type of currency used because they are ratios. For 5 Tons per day of sludge plant capacity, economic analysis gave 2 years Pay Back Period (PBP) and 47 % Rate of Return on Investment (ROI). This show that a petroleum sludge anaerobic digestion plant if well managed could economically viable in Nigeria.

5.0. CONCLUSION

Anaerobic digestion helps transform the toxic Petroleum sludge to harmless biosolids useful as fertilizer of higher quality than petrochemical based fertilizers. Biogas, being a renewable energy source and environmentally friendly is a better substitute for natural gas. Besides enhancing sustainable development and increasing the Nigerian Gross Domestic Product (GDP) anaerobic digestion of Petroleum sludge could optimize petroleum oil and gas production in Nigeria as the Nigerian oil and gas reserve is being maximized and total reliance on petroleum and natural gas as the only energy sources minimized. With anaerobic digestion of Petroleum sludge, Nigerian oil and gas reserves and net petroleum exports will increase. With anaerobic digestion plant as a process unit in every Nigerian Petroleum industry and waste water treatment plant, the problem of sludge treatment and disposal according to Environmental Protection Agency (EPA) standards and regulations will be solved.

6.0. RECOMMENDATIONS

It is recommended that:

i. Every Nigerian oil and gas industry must have an anaerobic digestion plant as a process unit in its Process plant and Waste Water Treatment Plant. Private investors and government are encouraged to invest in the anaerobic digestion plant considering its high economic viability and profitability.

ii. Biogas produced from anaerobic digestion be upgraded and its production maximised so that with rising natural gas exports, biogas could substitute natural gas as a domestic fuel source, being environmentally friendly and a renewable energy source, natural gas being exclusively for exports.

iii. The use of biosolids as fertilizer be encouraged and farmers made aware of its advantages over the petrochemical based fertilizer.
7.0. REFERENCES


### 8.0. NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
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<tbody>
<tr>
<td>$X_1$</td>
<td>Concentration of Biomass</td>
<td>$mg/L$</td>
</tr>
<tr>
<td>$t$</td>
<td>Time</td>
<td>hr</td>
</tr>
<tr>
<td>$D$</td>
<td>Dilution Rate</td>
<td>$(hr^{-1})$</td>
</tr>
<tr>
<td>$\mu_m$</td>
<td>Maximum Specific Growth Rate or Half Maximal Velocity Concentration</td>
<td>$(hr^{-1})$</td>
</tr>
<tr>
<td>$X_{1,0}$</td>
<td>Inlet Biomass Concentration</td>
<td>$mg/L$</td>
</tr>
<tr>
<td>$K_m$</td>
<td>Monod's constant</td>
<td></td>
</tr>
<tr>
<td>$X_2$</td>
<td>Sludge concentration</td>
<td>$mg/L$</td>
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<tr>
<td>$X_{2,0}$</td>
<td>Inlet Sludge Concentration</td>
<td>$mg/L$</td>
</tr>
<tr>
<td>$Y$</td>
<td>Yield Coefficient given as mass of sludge or biomass produced per unit biosolids removed</td>
<td>$(mgvSS/mgBCOD)$</td>
</tr>
<tr>
<td>$k_d$</td>
<td>Endogenous Respiration Coefficient or specific maintenance rate, per day</td>
<td>$(d^{-1})$</td>
</tr>
<tr>
<td>$S_0$</td>
<td>Biochemical Carbonaceous Oxygen Demand (BCOD) in the influent sludge</td>
<td>$(mg/L)$</td>
</tr>
<tr>
<td>$S$</td>
<td>Biochemical Carbonaceous Oxygen Demand (BCOD) in the effluent biosolids</td>
<td>$(mg/L)$</td>
</tr>
<tr>
<td>$V_{CH_4}$</td>
<td>Volume of Methane produced</td>
<td>$(m^3/d)$</td>
</tr>
<tr>
<td>$P_x$</td>
<td>Net Mass of Cell Tissue produced per day</td>
<td>$kg/d$</td>
</tr>
<tr>
<td>$E$</td>
<td>Efficiency of Sludge Utilization</td>
<td>$(0.6 - 0.9)$</td>
</tr>
<tr>
<td>$\theta_x$</td>
<td>Mean Cell Residence Time</td>
<td>$(days)$</td>
</tr>
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### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Meaning</th>
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<tr>
<td>BCOD</td>
<td>Biochemical Carbonaceous Oxygen Demand</td>
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<td>CFU</td>
<td>Colony Forming Unit</td>
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<tr>
<td>DF</td>
<td>Dilution Factor</td>
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<tr>
<td>EPA</td>
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<tr>
<td>GC – MS</td>
<td>Gas Chromatography and Mass Spectrophotometry</td>
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<tr>
<td>GDP</td>
<td>Gross Domestic Product</td>
</tr>
<tr>
<td>HRT</td>
<td>Hydraulic Retention Time</td>
</tr>
<tr>
<td>NAP</td>
<td>Net Annual Profit</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
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<td>--------------------------------------</td>
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<tr>
<td>NPK</td>
<td>Nitrate, Phosphate and Potassium</td>
</tr>
<tr>
<td>PAHs</td>
<td>Polycyclic Aromatic Hydrocarbons</td>
</tr>
<tr>
<td>PBP</td>
<td>Pay Back Period</td>
</tr>
<tr>
<td>PPM</td>
<td>Parts Per Million</td>
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<tr>
<td>PPU</td>
<td>Power Plant and Utilities</td>
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<tr>
<td>PSA</td>
<td>Pressure Swing Adsorption</td>
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<tr>
<td>ROI</td>
<td>Rate of Return on Investment</td>
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<tr>
<td>SRT</td>
<td>Solids Retention Time</td>
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<tr>
<td>TABC</td>
<td>Total Anaerobic Bacterial Count.</td>
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<tr>
<td>TI</td>
<td>Total Investment</td>
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<tr>
<td>THC</td>
<td>Total Hydrocarbon Content</td>
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<tr>
<td>VSS</td>
<td>Volatile Suspended Solids</td>
</tr>
<tr>
<td>WWTP</td>
<td>Waste Water Treatment Plant</td>
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