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Design of a Bioreactor for the Treatment of Petroleum Sludge

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ABSTRACT Untreated petroleum sludge constitutes health hazard to personnel on exposure and environmental hazard on disposal. The treatment of sludge destroys disease pathogens present in the sludge. Under microbial substrate limiting Mesophilic anaerobic digestion, a bioreactor for the treatment of 5 tons per day of sludge was designed. Dimensions of the bioreactor were obtained by substituting kinetic and experimental data into design equations. The potential of anaerobic digestion for the treatment of sludge was proved by a reduction in Biological Carbonaceous Oxygen Demand (BCOD) of the sludge from 6,080 mg/L to 20.40 mg/L and Total Hydrocarbon Content (THC) from 57,000 ppm to 1500 ppm. Gas Chromatography and Mass Spectrophotometry (GC-MS) result showed a decrease in concentration of priority Polycyclic Aromatic Hydrocarbons (PAHs) from 37.1mg/L to 0.32 mg/L Naphthalene; 33.43 mg/L to 8.24 mg/L Anthracene; 33.97 mg/L to 9.86mg/L Phenanthrene. Anaerobic digestion of 200 grams of sludge gave 10,500 m^3 /d biogas meaning 1 gram of sludge could yield 840 m^3 biogas for solids retention time of 16 days. The 183.50 m^3 Volume; 15.93 m high; 3.83 m diameter bioreactor design provided could help Nigerian industries and environmental agencies construct and install bioreactors for the treatment of their sludge at affordable cost. This will enhance Nigerian content in bioreactor manufacture and operation. With a bioreactor anaerobic digestion plant as a process unit in every Nigerian Process 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.

Keywords: Bioreactor, Sludge; Priority toxicants; Anaerobic Digestion; Biochemical Carbonaceous Oxygen Demand; Total Hydrocarbon Content

Introduction

Petroleum industries generate large quantities of sludge which is a major source of environmental pollution (Islam, 2015). Petroleum sludge constitutes health hazard to personnel on exposure and environmental hazard on disposal, if not properly treated before disposal. Besides this, it is an economic waste to dispose sludge without treatment as the treatment yields important products such as biogas, pharmaceuticals, fertilizers, etc (Appels *at al.,*2008). In this study, a Fed-batch bioreactor for the treatment of petroleum sludge is designed to make the sludge nontoxic to personnel on exposure, harmless to the environment on disposal. Islam (2015) states that petroleum sludges are hazardous wastes according to environmental protection act and hazardous waste handling rules. These sludges cannot be disposed of as landfills even if they are de-oiled unless they are totally remediated. These sludges have to be treated and made harmless before disposal. Sampson (2017) state that most Nigerian industries find it difficult to adhere to Environmental Protection Agency (EPA) Standards and Regulations for the treatment and disposal of sludge because they do not have bioreactors as an essential process unit in their process industries and waste water treatment plants. This is evidenced by numerous visits to most Nigerian process industries where sludges are heaped with the hope of incinerating them in a burn pit.

In Nigeria, hazardous wastes (sludge) have been dumped in various places e.g. Abattoir in Rivers State. The Nigerian government is recently embarking on clean-up of areas polluted with sludge e.g. Ogoni land in Rivers State. In Nigeria, the treatment and disposal of sludge imposes a major challenge to the oil and gas industry. This study has provided a solution to this problem as the relevant industries and environmental agencies can now make use of the design data to fabricate and install suitable bioreactors for the treatment of their sludge at affordable cost.

The treatment of sludge in bioreactors will eliminate the odour, health and environmental hazard associated with disposal of untreated sludge. Moreover, biogas a substitute for natural gas will be produced. This will enhance the realization of the Nigerian quest for self-sufficiency in renewable energy. This is not a mere speculation as biogas sources are not yet fully utilized in Nigeria as it is in the advanced countries (Emberga *etal*.,2014; Osai,2012; Fasina&Simonyan,2013; Temilade, 2008). Kavitha & Pharm (2006) state that continuous stirred tank bioreactors are constructed according to recognized standards as published by International Standards Organization and British Standards Institute. These dimensions consider both mixing, effectiveness and structural consideration. A mechanically stirred tank bioreactor is filled with a rushton turbine type impeller.

Fig. 1: Pictorial view of a Bioreactor
Source: Wikipedia (2014)

Rao (2010) gives a generalized model for a Fed-batch bioreactor as in equation (1)

$$\frac{dC_i}{dt} = \frac{V(t)}{V_{Rc}}\left(C_{i,o} - C_i\right) + r_{fi} \quad (1)$$

Green & Perry (1997) states that the sludge is first hydrolysed to become water soluble and then degraded to produce volatile organic acids primarily acetic acid and hydrogen. *Methanogenic* bacteria then split the acetic acid to methane and carbondioxide (biogas).

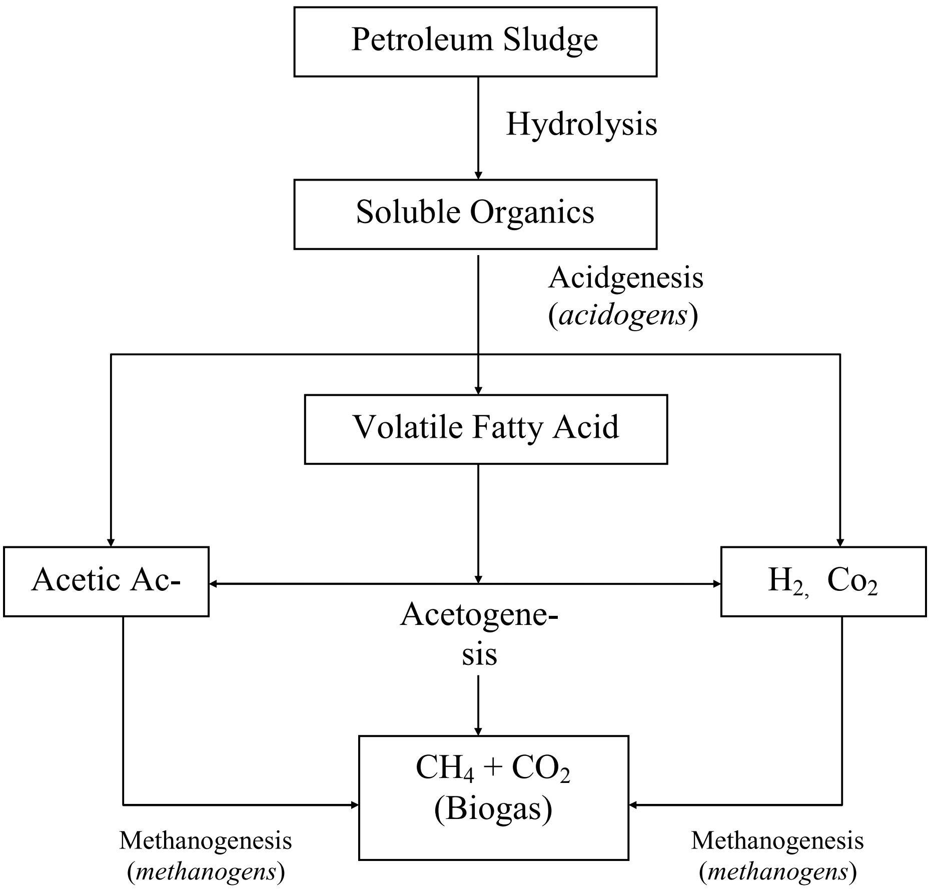


Fig.2: Steps in anaerobic digestion process of Petroleum sludge
Source: Appels *et al.* (2008)

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. Technical & Regulatory Guideline (2006) states that *methanogenic* bacteria prefer a relatively neutral pH of 6.6 to 7.4 and not acidic conditions. If acid formation is excessive the activity of the *Methanogenic* bacteria can be inhibited.

It is good practice to destroy the volatile acids as quickly as they are produced otherwise the volatile acids build up and depress the pH and eventually inhibit the *methanogenic* bacteria. To prevent this occurrence feed to the digester should be as uniform as possible and at short intervals as possible. Appels *et al.* (2008) gives the steps to sludge biodegradability as follows: Hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis among this, Hydrolysis is the rate limiting step.This rate limiting hydrolysis is enhanced by biological, chemical and mechanical interventions to the sludge. These interventions result in lysis or disintegration of sludge cells hence transforming the sludge into a biodegradable material. Hence, a test for the rate of biodegradability of sludge species, results in experimental data which fit into equations developed from kinetic models.

Anaerobic digestion results in the conversion of the biodegradable sludge to methane, carbon dioxide and microbial cells. Volatile suspended solids (VSS) produced are quite low. Biological carbonaceous oxygen demand (BCOD) is destroyed. Biogas produced range from 50 to 80 percent methane and 20 to 50 percent carbon (iv) oxide (CO_2) depending on the chemical characteristics of the sludge digested. The biogas produced is important for heat and power generation.
The pH should be maintained at 6.5 - 7.5 with the help of hydrochloric acid to avoid free ammonia toxicity. The use of nitric or sulphuric acid could result in significant operational problems.

Design Equations

Mass of Biological Solids
The mass of biological solids can be calculated using a relationship from Tchobanoglous *et al.* (2004)

$$P_x = \frac{\left[YQ(s_o - s)(10^3 g/kg)^{-1}\right]}{[1 + k_d(SRT)]} \tag{2}$$

Percent Volatile Solids Destroyed
The percent volatile solids destroyed can be calculated using a relationship from Tchobanoglous *et al.* (2004)

$$V_d = 13.7\, ln(SRT) + 18.9 \tag{3}$$

Volume of Methane
The volume of Methane can be calculated using a relationship from Tchobanoglous *et al.* (2004)

$$V_{CH4} = (0.35)[(s_o - s)(Q)(10^3 g/kg)^{-1} - 1.42P_x] \quad (4)$$

Materials and Methods

Materials

The following materials were used for the study:
Dissolved oxygen reagent bottles, Mineral water, 25ml density bottle, Hanna pH meter H196107, Muffle furnace LMF4, Thermospectronic spectrophotometer 4001/4, Oven, Gallenkamp incubator, Autoclave, Labtech anaerobic jar, Olympus microscope, Agilent gas chromatography and mass spectrophotometer (GC-MS) 7890 B, Spectr AA 55 B atomic absorption spectrophotometer, Petroleum sludge collected from a typical Petroluem Industry in Port Harcourt, Nigeria. *Methanogenic* Bacteria *(Methanobrevibacter)* isolated from the intestine of cow. OxoidAnaero Gen TM AN 0035A gas Park used in labtech anaerobic Jar to create anaerobic condition, Winkler reagent A & B.

Methods

200 grams of the sludge was measured using a chemical balance and put into a beak- er. 2 grams of *methanogenic methanobrevibacter* bacteria was pip petted and put into the sludge in the beaker after which the beaker was put into labtech anaerobic jar with improvise for gas collection point. Anaerobic condition was maintained with the help of oxoid Anaerobic Gen TM AN 0035A gas park and catalyst. The anaero- bic jar was corked airtight and kept in a Gallenkamp incubator maintained at 37^0C (mesophilic) for a solids retention time of sixteen days. After performing a ten-fold serial dilution; the Total Anaerobic Bacterial Count in cfu/g was calculated using the equation (5)

$$TABC = \frac{1}{DF} \times Average\ of\ plate\ bacterial\ count \times \frac{1}{Volume\ Correction\ factor} \quad (5)$$

The percent Volatile Suspended Solids (VSS) measured using gravimetric method was calculated using equation (6)

$$Volatile\ Suspended\ solids = \frac{Weight\ of\ Volatile\ residue}{Weight\ ofresidue} \times \frac{100}{1} \quad (6)$$

The Total Hydrocarbon Content (THC) measured using spectrophotometric method was calculated using equation (7)

$$THC = \frac{Absorbance\ of\ sludge \times Gradient\ of\ standard\ graph}{weight\ of\ sample\ diluted\ in\ 100ml \times \frac{1}{Dilution\ Factor}} \quad (7)$$

The Biochemical Carbonaceous Oxygen Demand (BCOD) measured using the Win- kler's method was calculated using the equation (8)

$$BCOD_5 = \frac{DO_{initial} - DO_{Final}}{DilutionFactor} \quad (8)$$

The concentration of Polycyclic Aromatic Hydrocarbons (PAHs) in the sludge and in the biosolids produced from anaerobic digestion of the sludge was measured using Gas Chromatography – Mass Spectrophometry (GC-MS).

Model Development

Using the unsteady state materials balance for the substrate and biomass:

For Biomass:

$$[Flow\ of\ materials\ in] = FX_{1,0} \quad (9)$$

$$[Microbial\ biodegradability] = RX_1V = \mu X_1 V \quad (10)$$

Where R is the rate of microbial biodegradation.

$$[Flow\ of\ materials\ out] = FX_1 \quad (11)$$

$$Accumulation = \frac{d(vX_1)}{dt} = \frac{vdX_1}{dt} \quad (12)$$

From material balance:

Flow of materials in + Microbial biodegradability of sludge - Flow of materials out = Accumulation

$$\frac{vdX_1}{dt} = Fx_{1,0} + \mu X_1 V - FX_1 \quad (13)$$

Dividing through by V

$$\frac{V}{V}\frac{dX_1}{dt} = \frac{FX_{1,0}}{V} + \mu X_1 \frac{V}{V} - \frac{FX_1}{V} \quad (14)$$

Take out $\frac{F}{V}$ because it is common.

$$\frac{dX_1}{dt} = \frac{F}{V}(X_{1,0} - X_1) + \mu X_1 \quad (15)$$

$$\frac{dX_1}{dt} = D\left(X_{1,0} - X_1\right) + \mu X_1 \quad (16)$$

Where D is the dilution rate

$X_{1,0}$ is the inlet biomass concentration, mg/L

X_1 is the biomass concentration, mg/L

Writing equation (16) in the pattern of Monods Kinetic Model:

$$\frac{dX_1}{dt} = D\left(X_{1,0} - X_1\right) + \frac{\mu m X_1 X_2}{k_m + X_2} \quad (17)$$

Where μ_m is the maximum specific growth rate (hr^{-1})

X_2 is the sludge concentration, mg/L

For the Sludge

$$[Flow\ of\ materials\ in] = FX_{2,0} \tag{18}$$

Where $X_{2,0}$ is the inlet sludge concentration

Microbial biodegradability of the sludge = $R\,X_2V$

$$= \frac{1}{Y}RX_1V = -\frac{\mu X_1 V}{Y} \tag{19}$$

R is the rate of microbial biodegradation.

$$[Flow\ of\ materials\ in] = FX_2 \tag{20}$$

$$\text{Accumulation} = \frac{VdX_2}{dt} \tag{21}$$

From the materials balance equation:

Accumulation = Flow of materials in + Microbial biodegradability of sludge – flow of materials out.

We have:

$$\frac{VdX_2}{dt} = Fx_{2,0} - \frac{\mu X_1 V}{Y} - FX_2 \tag{22}$$

$$\frac{VdX_2}{dt} = F(X_{2,0} - X_2) - \frac{\mu X_1 V}{Y} \tag{23}$$

Dividing through by V:

$$\frac{VdX_2}{Vdt} = \frac{F}{V}(x_{2,0} - x_2) - \frac{\mu X_1}{Y}\frac{V}{V} \tag{24}$$

$$\frac{dX_2}{dt} = D\left(x_{2,0} - x_2\right) - \frac{uX_1}{Y} \tag{25}$$

Writing it to conform with the pattern of Monods equation:

$$\frac{dX_2}{dt} = D\left(X_{2,0} - X_2\right) - \frac{\mu_m X_1 X_2}{Y(k_m + X_2)} \tag{26}$$

Where F is the volumetric flow rate of the feed and *D* is the dilution rate per hour, (hr^{-1}) and Y is the yield coefficient.

Writing equation (16) & (25) in the pattern of the substrate inhibition kinetic model, we obtain:

$$\frac{dX_1}{dt} = D\left(X_{1,0} - X_1\right) + \frac{\mu_m X_1 X_2}{k_m + X_2 + \frac{X_2{}^2}{K_1}} \tag{27}$$

$$\frac{dX_2}{dt} = D\left(X_{2,0} - X_2\right) - \frac{\mu_m X_1 X_2}{Y\left(K_m + X_2 + \frac{X_2{}^2}{K_1}\right)} \qquad (28)$$

Where K_1 is the inhibition constant.

Note that for sterile feed conditions $X_{1,0} = 0$

Writing equation (17) in the pattern of the modified form of Monods equation

$$\mu = \frac{\mu_m X_2}{k_m + X_2} - kd$$

We obtain equation in the form:

$$\frac{dX_1}{dt} = D\left(X_{1,0} - X_1\right) + \frac{\mu_m X_1 X_2}{k_m + X_2} - k_d X_1 \qquad (29)$$

Recall equation (1)

$$\frac{dC_i}{dt} = \frac{V_t}{V_{RC}}\left(C_{i,0} - C_i\right) + r_{fi}$$

For Biomass:

Recall equation (29)

$$\frac{dX_1}{dt} = D\left(X_{1,0} - X_1\right) + \frac{\mu_m X_1 X_2}{k_m + X_2} - k_d X_1$$

$X_{1,0}$ is inlet biomass concentration

For the Sludge:

Recall equation (26)

$$\frac{dX_2}{dt} = D\left(X_{2,0} - X_2\right) - \frac{\mu_m X_1 X_2}{\gamma(k_m + X_2)}$$

$X_{2,0}$ is inlet sludge concentration

Comparing it with fed-batch bioreactor equation of (Rao, 2010)

$$\frac{dC_i}{dt} = \frac{V_t}{V_{RC}}\left(C_{i,0} - C_i\right) + r_{fi}$$

Dilution rate = $V_t / V_{RC} = D$

From equation (29)

For Biomass:

$$r_{fi} = +\frac{\mu_m X_1 X_2}{K_m + X_2} - k_d X_1 \qquad (30)$$

The positive sign depicts that the biomass is multiplying.
From equation (26)

For Sludge:

$$r_{fi} = -\frac{\mu_m X_1 X_2}{\gamma(K_m+X_2)} \qquad (31)$$

This gives the rate of reaction. The negative sign depicts that the sludge is biodegrading.

Note that no $K_d X_1$ is included in the r_{fi} for sludge because K_d, the endogenous respiration coefficient is zero for the sludge. $\frac{dx_2}{dt} = \frac{\mu_m x_1 x_2}{Y(km+x_2)}$ gives the rate of reaction rf_i. Therefore equation (1) can be written in another form as:

$$\frac{dX_2}{dt} = D\left(X_{2,0} - X_2\right) - \frac{\mu_m X_1 X_2}{\gamma(K_m + X_2)}$$

Design Equations

Levenspiel (2001) give rate of reaction as

$$-r_A = KC_A \qquad (32)$$

But $C_A = C_{A_O}$ (1 - X_A) (33)

$$-r_A = KC_{A_O} (1 - X_A) \qquad (34)$$

Substitute this for $-r_A$ in the equation obtained from Levenspiel (2001)

$$V_R = \frac{NA_o}{t}\int_0^{XA} \frac{dX_A}{(-r_A)} \qquad (35)$$

$$V_R = \frac{NA_o}{t}\int_0^{XA} \frac{dX_A}{KCA_o(1-X_A)} \qquad (36)$$

$$V_R = \frac{NA_o}{tKCA_o}\int_0^{XA} \frac{dX_A}{(1-X_A)} \qquad (37)$$

Substituting K_m for K, K_m $X_{2,0}$ for C_{A_O} and considering the fractional change in volume

$$V_R = \frac{NA_o}{tK_m X_{2,0}}\int_0^{XA} \frac{dX_A}{(1-X_A)(1+E_A X_A)} \qquad (38)$$

Where V_R is the volume of the Bioreactor

Yield coefficient was calculated using equation given in Econotres (2014)

$$\text{Yield Coefficient (Y)} = \frac{mgVSS}{mg\ BCOD} \tag{39}$$

Appels *et al*. (2008) give equation for Net mass of cell tissue produced per day:

$$P_x = \frac{YES_0}{1 + k_d\theta_c} \tag{40}$$

Volume of Biogas produced was calculated using equation (4)

$$V_{CH4} = (0.35)(S_0 - s)(Q)(10^3\ g/kg)^{-1} - 1.42P_x$$

Tapobrata (2011) give the following equations for bioreactor fundamental dimensions:

Height of Bioreactor

$$h = \frac{4V_R}{\pi D^2} \tag{41}$$

Impeller Diameter of Bioreactor

$$\frac{D_i}{D} = 0.3 \tag{42}$$

$$D_i = D \times 0.3$$

Width of Baffle

$$(0.08 - 0.1)D_i \tag{43}$$

Length of Jacket

$$J_L = \frac{1}{4}H \tag{44}$$

Vertical Distance between adjacent stirrer blades

$$\frac{I_L}{D_i} = 1.2 \tag{45}$$

$$\text{Poison ratio} = \frac{\text{hemispherical thickness}}{\text{Cylinder thickness}} \tag{46}$$

$$\textbf{Volume of hemisphere} = \frac{2}{3}\pi \times r^3 \div 2 \tag{47}$$

$$\textbf{Volume of conical bottom} = \frac{1}{8}V_R \tag{48}$$

$$\textbf{Height of conical bottom} = \frac{1/8V_R \times 3}{\pi r^2} \quad (49)$$

Results

The Plant Capacity
5 tons per day; 1,500,000 kg per annum; 625 kg per hour

Data Obtained

Table 1: Data Obtained

Parameter	Value
Initial concentration of Biomass $(X_{1,0})$	$1.0\ mg/l$
Initial concentration of sludge $(X_{2,0})$	$0.3383\ mg/l$
Volatile suspended solids (VSS)	99.6 %
Biochemical carbonaceous oxygen demand (influent sludge)	$6080\ mg/l$
Yield coefficient (Y)	0.016
Maximum specific growth rate (μ_m)	$0.0738\ hr^{-1}$
Dilution rate (D) or space velocity	$0.18\ hr^{-1}$
Space time	5.5555 hrs
Negative of log of Hydrogen ion Concentration (pH)	6.5
Specific Gravity	$0.95472\ g/ml$
Percent Volatile Solids	96.50 %
Percent Total Solids	97.30 %
Monods Constant (K_m)	$0.02\ kmol/m^3$
Endogenous respiration Coefficient (K_d)	$0.025\ d^{-1}$

A MATLAB program in fourth order Rungekutta gave the following result

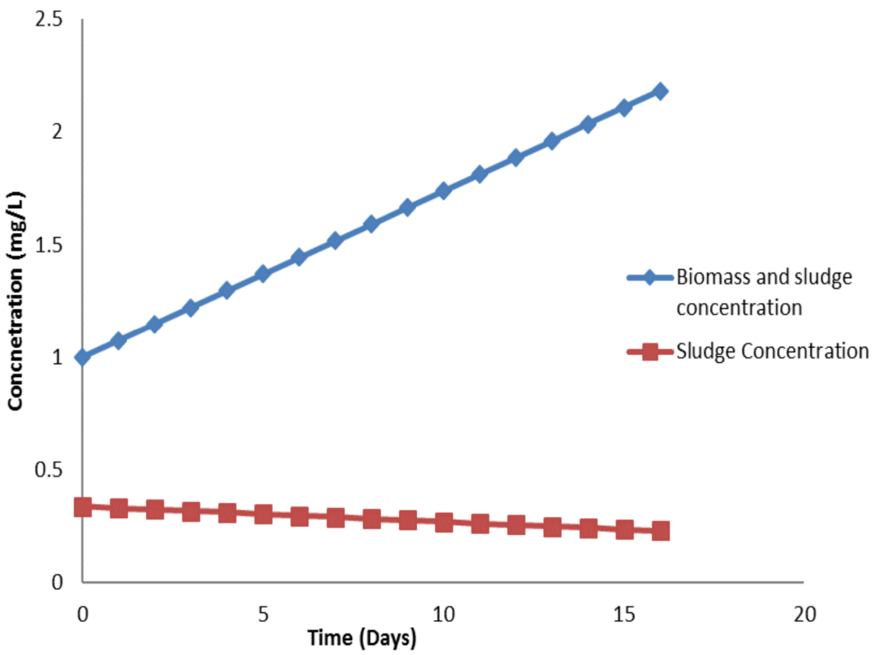


Fig. 3: Rate of sludge biodegradation and biomass multiplication

Biochemical Carbonaceous Oxygen Demand and Total Hydrocarbon Content

Table 2: Biochemical Carbonaceous Oxygen Demand and Total Hydrocarbon Content

DAYS	1	4	16
$BCOD/(mg/l)$	6080	1200	20.40
$THC(ppm)$	57000	30,000	1500

Polycyclic Aromatic Hydrocarbons

Table 3: GC – MS for the priority toxicants in the petroleum sludge

Toxicant	CONCENTRATION (mg/L)	
	Untreated Sludge	**Biosolids**
Napthalene	37.1	0.32
Anthracene	33.43	8.24
Phenanthrene	33.97	9.86

GC-MS Waveforms

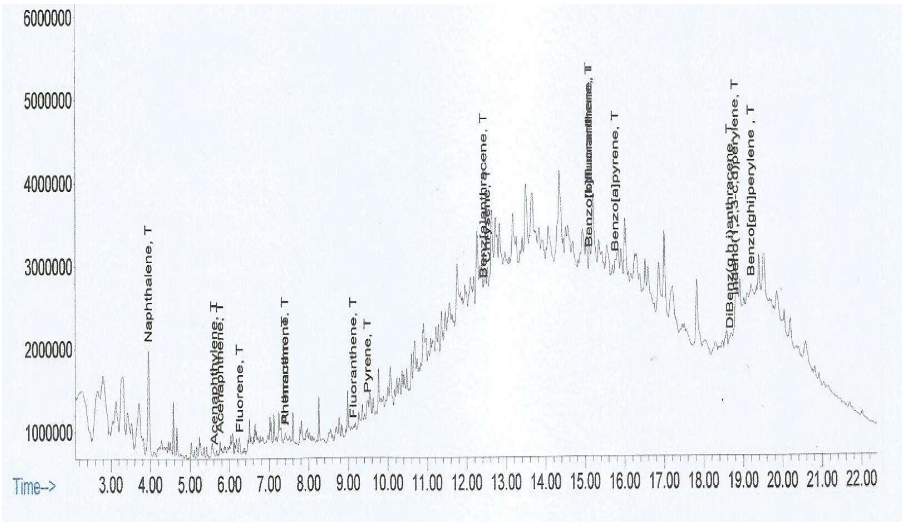


Fig.4: Waveform for GC-MS analysis of petroleum Sludge

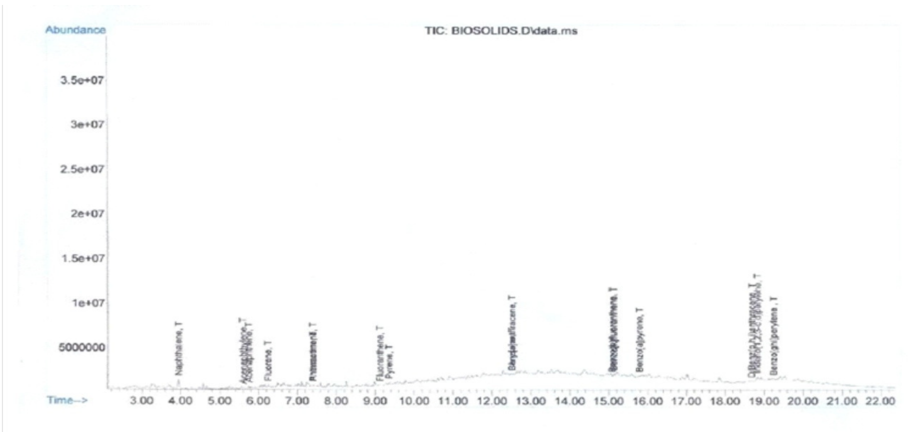


Fig.5: waveform for GC-MS analysis of Biosolids

Volume of biogas produced

Table 4: Volume of Biogas Produced

Influent BCOD (mg/l)	Effluent BCOD (mg/l)	Flow rate of Biogas (m^3/d)	Net mass of cell Tissue Produced Per day (kg/d)	Volume of Biogas m^3/d	Volume of Biogas from one gram of sludge (m^3)
6080	20.4	5000	62.54	10,500	840

Sizing the Bioreactor

Quist (2007) give equation (50):

$$C_5H_7O_2N + 4H_2O \xrightarrow{Methanobrevibacter} 1.5CO_2 + 2.5CH_4 + NH_4^+ + HCO_3^- \quad (50)$$

Where ε_A is given by

$$\Sigma CR : 1 + 4 = 5$$
$$\Sigma CP : 1.5 + 2.5 + 1 + 1 = 6$$

$$\varepsilon_A = \frac{\Sigma CP - \Sigma CR}{\Sigma CR} \qquad \varepsilon_A = \frac{6-5}{5}$$

$$\varepsilon_A = \frac{1}{5} = 0.2$$

Levenspiel (2001) give formula for conversion

$$X_A = 1 - \frac{CA}{CAo}$$

$$X_A = 1 - \frac{X_2}{X_{2,0}}$$

$X_{2,0} = 0.3383$ mg/l
$X_2 = 0.228893$ mg/l

$$X_A = 1 - \frac{0.2289}{0.3383}$$

$$X_A = 1 - 0.6766$$

$X_A = 0.3234$

Coulson & Richardson (1991) give the Monods constant
Km : 0.02 mol/m^3
t: solids retention time, 16 days
C_{Ao}: initial concentration of sludge
$C_{Ao} = X_{2,0}$ = 0.3383
N_{Ao}: Number of moles of sludge
Molar mass of $C_5H_7O_2N$: (12×5) + (1×7) + (16×2) + (14×1) = 6+7+32+14=113

Plant Capacity: Given a Plant capacity of 5 Tons per day. Knowing that 1Ton is equivalent to 1000 kg, So 5 Tons is equivalent to 5000 kg which is the mass of sludge digested per day.

$$= \frac{\text{Mass}}{\text{Molar Mass}} = \frac{5000\text{kg}}{113}$$

= 44.24778761 kmol/day
= 44.24778761×10^3 moles/day
= 44,247.78761 moles/day

Recall equation (38)

$$V_R = \frac{N_{AO}}{C_{AO}.\text{t.Km}} \int_0^{XA} \frac{dX_A}{(1 - xA)(1 + \varepsilon_A X_A)}$$

Substituting $X_{2,0}$ for C_{A0} in eqn (38) $X_{2,0} = C_{A0}$

$$V_R = \frac{N_{Ao}}{X_{2,0}tKm} \int_0^{0.3234} \frac{dX_A}{(1 - XA)(1 + \varepsilon_A X_A)}$$

$$V_R = \frac{44{,}247.78761}{0.3383x16x0.02} \int_0^{0.3234} \frac{d\,(0.3234)}{(1 - 0.3234(1 + 0.2x(0.3234)}$$

X_A = 0.3234
K_m = 0.02 mol/m^3
C_{Ao} = 0.3383 mg/L
t = 16 days
N_{Ao} = 44,247.78761 moles/day
ε_A = 0.2

Using MATHCAD Software
$V_R = 1.835 \times 10^5$ Litres
(1000 liters = 1m^3)

Therefore: $V_R = \frac{1.835 \times 10^5}{1000} = \frac{1,83500.00}{1000}$
= 183.50 m^3
Volume of Bioreactor = 183.50 m^3

Optimisation

Coulson & Richardson (2009) give equation for purchased equipment cost.

$$PEC = a + b\,s^n \times \text{MF} \quad (51)$$

Where:

PEC is the purchased equipment cost a & b, cost constants peculiar to the equipment.

s, the characteristics size parameter

n, the index characteristic of equipment size
Recall that:

$a = 28{,}000$ in 2010

That is, $28{,}000$ mutiplied by 1.96 in 2017 is equal to $54{,}880$

Range for b: 0 to 104,000

s is same for 2017 as it was in 2010

$s = 0.5$

n is same for 2017 as it was in 2010.

$n = 0.8$

MF, materials factor for stainless steel $= 1.3$ multiplied by 1.96 in 2016 is equal to 2.548

≈ 2.55 in 2017

Table 5: Optimization of Bioreactor Diameter

Diameter D (m)	a	b	s	bs	$a+b$	$a+bs$	n	bs^n	MF	$a+bs$	Cost $a+bs^n$ MF
0.5	6,875	12,985	0.5	6,492.5	19,860	13,367.50	0.8	1,121.84	2.55	7996.84	20,391.93308
1.0	13,750	25,970	05	12,985.0	39,720	26,735	0.8	1,953.23	2.55	15,703.23	40,043.23854
1.5	20,625	38,955	0.5	19,477.50	59,580	40,102.5	0.8	2,701.63	2.55	23,326.64	59,482.91762
2.0	27,500	51,940	0.5	25,970.0	79,440	53,470	0.8	3,400.77	2.55	30,900.77	78,796.96947
2.5	34,375	64,925	0.5	32,462.50	99,300	66,837.5	0.8	4,065.42	2.55	38,440.42	98,023.0746
3.0	41,250	77,910	0.5	38,955.0	119,160	80,205	0.8	4,703.82	2.55	45,953.82	117,182.2375
3.5	48,125	90,895	0.5	45,447.50	139,020	93,572.5	0.8	5,321,18	2.55	53,446.18	136,287.7605
4.0	55,000	103,880	0.5	51,940.0	158,880	106,940	0.8	5,921.09	2.55	60,921.09	155,348.7758

Interpolation for the Diameter of the Bioreactor at £ 148,906.4103 gave 3.83 meters.

Table 6: Bioreactor Fundamental Dimensions

Parameter	Value
Volume of the Bioreactor (V_R)	$183.50\ m^3$
Diameter of the Bioreactor (D)	$3.83\ m$
Height of Bioreactor (H)	$15.93\ m$
Impeller Diameter of Bioreactor (D_i)	$1.149\ m$
Width of Baffle (W_b)	$11.49\ cm$
Length of Jacket (J_L)	$3.9825\ m$
Vertical distance between adjacent stirrer blades (I_L)	$1.3799\ m$
Radius of Hemispherical head	$1.915\ m$
Height of Hemispherical head	$1.0\ m$
Radium of conical bottom	$1.915\ m$
Height of conical bottom	$6.0\ m$

Design Features

Material of Construction

Stainless steel does not easily get corroded.

Wall Thickness

Coulson & Richardson (2009) give $14mm$ as the minimum thickness for a vessel of diameter $3.5mm - 4.0mm.$

Wall thickness of bioreactor $= 14\ mm.$

Vessel Pressure

Coulson & Richardson (2009) give a pressure of 1 bar for vessels operated anaerobically. Pressure = 1 bar.

Spacing between the jacket and vessel wall
The spacing between the Jacket and vessel wall is 50 mm

Thickness of Jacket
Thickness of Jacket or lagging is 50 mm.

Lagging Material: Foam glass (Cellular glass made by fusing powered glass with Carbon particles.)

Cover for Lagging: Aluminium metal sheet (0.5 mm thick).

Support: Concrete pillars.

Stirrer Driver: Rushton turbine

Hemispherical Head

Poison ratio = $\frac{\text{Hemispherical head thickness}}{\text{cylinder thickness}}$

Radius of hemispherical head
Radius of cylinder = 1.915 meters, and equal to the radius of hemispherical head.

3.8.10.2. Height of Hemispherical head

Take volume of hemisphere to be $\frac{1}{3}$ volume of cylinder.

Volume of hemisphere (half of a sphere) $= \frac{2}{3} \times \pi \times r^3 \div 2$

Radius of the hemisphere $= 1.915\ metres$
Therefore:

Height of the hemisphere $= \frac{1.915}{2} = 0.9575 \approx 1.0\ metres$

Conical Bottom

Radius of conical bottom

Radius of Conical Bottom is same as radius of cylinder $= 1.915\ metres.$
Volume of the conical bottom is one eight the volume of the cylinder.

Volume of cylinder $= 183.50\ m^3$

Height of Conical Bottom
Volume of the conical bottom is one eight the volume of the cylinder.

Volume of cylinder $= 183.50\ m^3$

Volume of conical bottom: $\frac{1}{8} \times 183.50\ m^3 = 22.9375\ m^3$

Volume of conical bottom $= \frac{1}{3}\pi r^2 h$

$$22.9375 = \frac{1}{3} \times 3.142(1.915)^2 h$$

$$68.8125 = 11.52242095h$$

$$h = \frac{68.8125}{11.52242095}$$

$$h = 5.972052253\ metres$$

$$h \approx 6.0\ metre$$

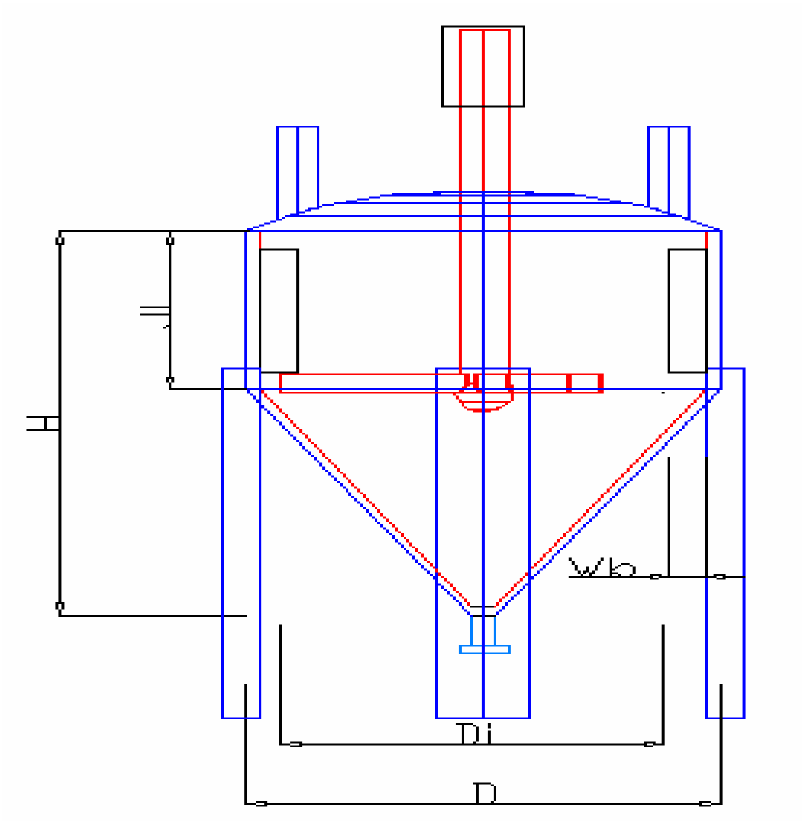
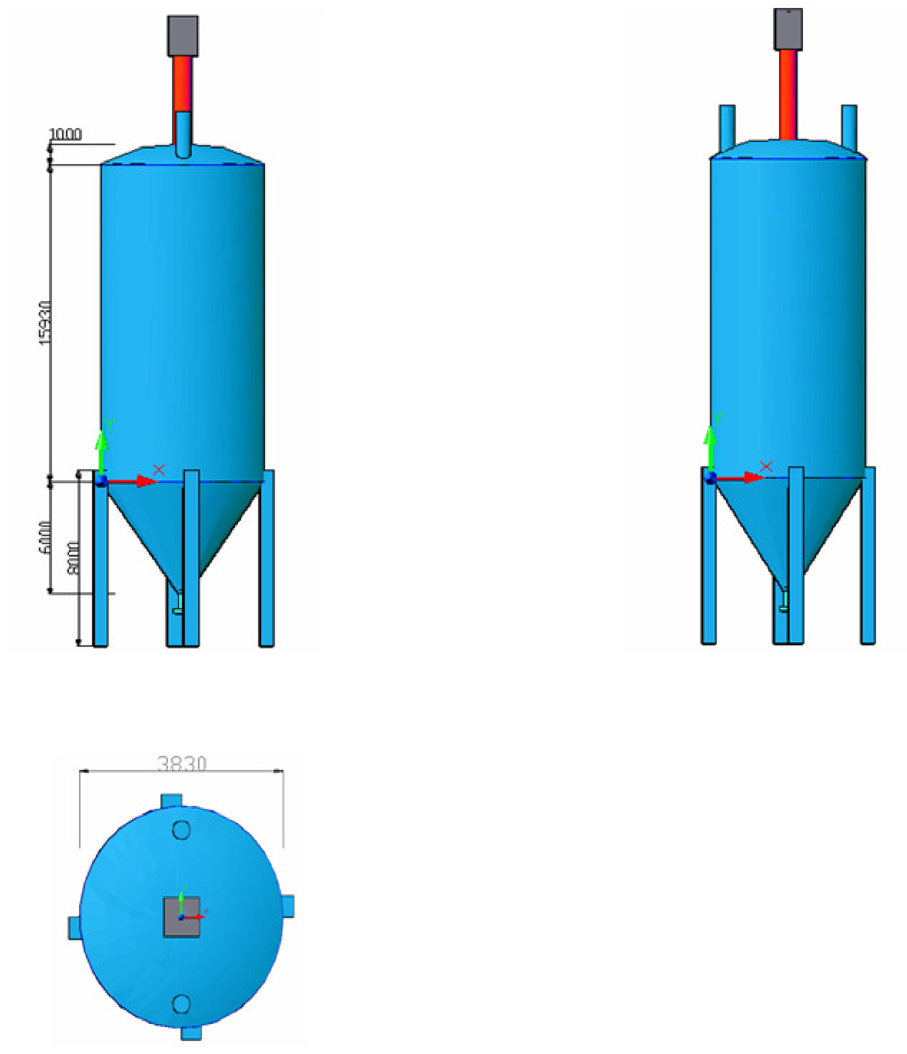


Fig.6: Bioreactor for Construction



Scale: 1m:1000mm

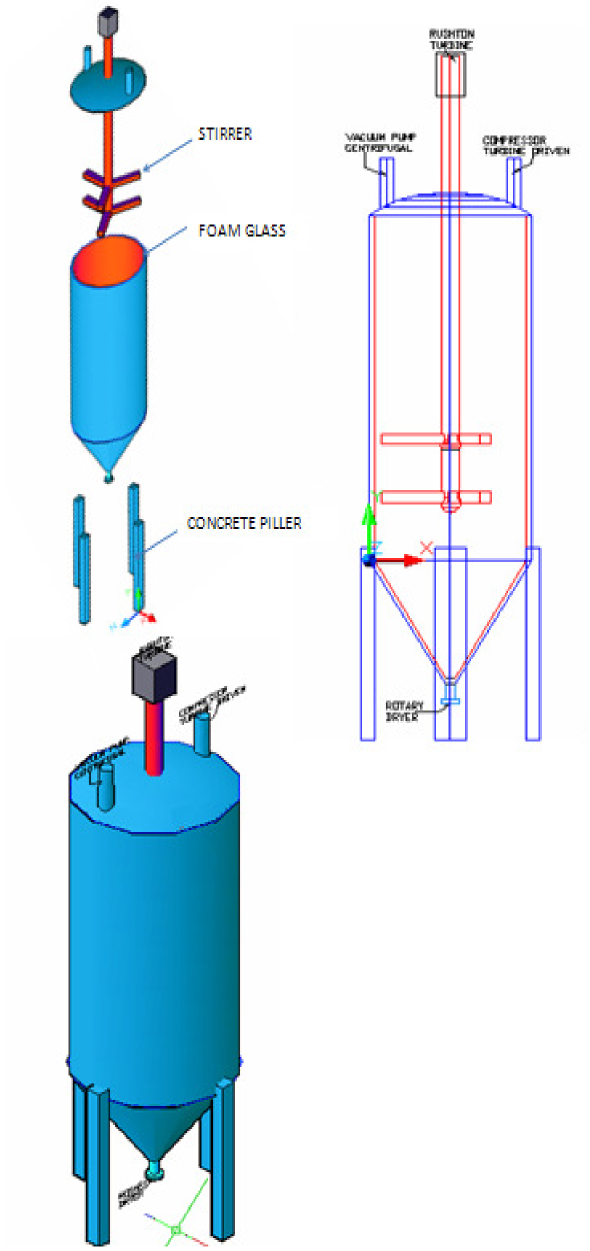


Fig. 8: Exploded views and 3-Dimensional view of the Bioreactor

Discussion

Assuming that due to constraints and operational problems, the plant is likely to run for 300 days per year. The plant capacity 5 tons per day which is equivalent to 5,000 kg per day gives 1,500,000 kg per annum. Assuming that the plant runs eight hours in one day because the workers are not put on shifting duties as well as intermittent shut downs for test run and maintenance jobs. The Plant capacity expressed per hour is equal to $625\ kghr^{-1}$. This plant capacity level is medium and hence suitable for semi-continuous flow processes such as fed-batch.

The result of the TABC indicates that micro-organisms multiplied in the biological reaction. The microbial digestion was terminated after 16 days at the falling rate phase when most of the micro-organisms must have died.

Table (2) show that BCOD and THC decreases with sludge biodegradation. BCOD and THC can therefore be used as a measure of sludge biodegration.

Table 3 show that the concentration of Napthalene, Anthracene and phenanthrene in the untreated sludge reduced from Thirties to Units after the sludge treatment.

According to Owabor & Owhiri (2011) Napthalene, 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.

A reasonable volume of biogas can be produced in substantial amount from anaerobic digestion of the sludge as shown in analysis of equation (4). 200 g sludge yielded 10,500 m^3/d biogas for 16 days. Considering 200 days operation per year. 1g sludge would yield 10,500/200=52.5 m^3/d biogas for 16 days.52.5×16 = 840 m^3 biogas from 1g of sludge.

Treatment of sludge is a slow reaction hence conversion must be low.

Coulson & Richardson (2009) State that Spacing between jacket and vessel wall must be high enough to enhance insulation.

Lagging must be thick enough to enhance heat conservation.

Foam glass is chosen as lagging material because foam glass is dense enough to allow for attachment of fittings and sealing and does not absorb moisture. Aluminum is chosen as cover for lagging because aluminum is cheap enough and is non-corrosive.

Concrete pillars are chosen as support because concrete pillars cannot conduct electricity. Rush ton turbine is chosen as stirrer driver because rush ton turbine is more robust and has higher efficiency.

A hemispherical head is used because a hemispherical head is the strongest shape, capable of resisting about twice the pressure of a *torispherical* head of the same thickness (Coulson & Richardson, 2009).

Conical bottom is used to facilitate the smooth flow and removal of solids from a process equipment (Coulson & Richardson, 2009). A bioreactor of volume 183.50 m^3, diameter 3.83metres and height 15.93 metres can be constructed as shown in figures 6, 7 and 8. However, the bioreactor can be scaled-up or scaled-down or re-modified to meet the needs of an industry or agency.

Conclusion

A bioreactor with the following fundamental dimensions: Volume 183.50 m^3; diameter 3.83 metres; height 15.93 metres has been designed. Other dimensions of the designed bioreactor are: impeller diameter 1.149 metres; width of baffle 11.49 cm; length of jacket 3.9825 metres; vertical distance between adjacent stirrer blades 1.3788 metres; wall thickness 14 mm; spacing between jacket and vessel wall 50 mm; thickness of jacket 50mm; Radius of hemispherical head 1.915 metres; Height of hemispherical head 1.0 metre; Radius of conical bottom 1.915 metres; Height of conical bottom 6.0 metres. With this design, the problem of sludge treatment in accordance with EPA standards and regulations for the treatment and disposal of sludge has been solved. The relevant industries and environmental agencies can now fabricate and install bioreactors for the treatment of their sludge at affordable cost. This could enhance Nigerian content in Bioreactor manufacture and operation, increase the Nigerian Gross Domestic Product (GDP) hence advancing the Nigerian Economy. The potential of anaerobic digestion for the treatment of petroleum sludge has been proved by a decrease in the concentration of polycyclic aromatic hydrocarbons. The priority toxicants in the sludge (Naphthalene, Phenanthrene and anthracene) decreased in concentration from thirties to units. The biochemical carbonaceous oxygen demand decreased from $6080\ mg/l$ to $20.40\ mg/l$ and the total hydrocarbon content of the sludge from 57000 ppm to 1500 ppm. Hence anaerobic digestion helps to transform the toxic petroleum sludge to harmless biosolids. It was found that the treatment of 5 Tons per day of petroleum sludge could yield $10{,}500\ m^3$ per day of biogas; hence, one gram of the sludge could yield $840m^3$ biogas for a solid retention time of sixteen days. Biogas, being a renewable energy source and a better substitute for natural gas, anaerobic digestion of petroleum sludge could enhance the realization of the Nigerian quest for self sufficiency in sustainable energy. The plant should be located as a process unit in every Nigerian process industry, waste water treatment plants and sites where sludge is dumped.

Recommendations

The following recommendations are made:

i. Biogas produced from anaerobic digestion can be upgraded and its production maximized 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.

ii. Considering that Nigerian industries and environmental agencies could not treat their sludge because of high treatment cost, it is necessary that local design, construction and installation of the anaerobic digestion plant be carried out as this could help Nigerian industries and environmental agencies treat their sludge at affordable cost.

The above recommendations can easily be implemented with the present call for amendment of the Nigerian Petroleum Industry Law. Nigerian vision 2020 of zero gas flaring could be realized if sludge incineration in Nigerian industries is stopped with the adoption of the anaerobic digestion process technology.

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APPENDIX

Abbreviation	Definition
BCOD	Biological Carbonaceous Oxygen Demand
SRT	Solids Retention Time
cfu	Colony Forming Unit
DF	Dilution Factor.
DO	Dissolved Oxygen
EPA	Environmental Protection Agency
EU	European Union
FAO	Food and Agricultural Organization
GC – MS	Gas Chromatography and Mass Spectrophotometry
GDP	Gross Domestic Product
MF	Materials Factor
PAHs	Polycyclic Aromatic Hydrocarbons
PEC	Purchased Equipment Cost
SRT	Solids Retention Time
TABC	Total Anaerobic Bacterial Count
THC	Total Hydrocarbon Content
VSS	Volatile Suspended Solids
WWTP	Waste Water Treatment Plant

Nomenclature

Symbol	Definition	Unit
C_i	Inlet concentration	$kmol/m^3$
C_i,o	Initial concentration of component	$kmol/m^3$
D_i	Impeller diameter	m
E	Efficiency of sludge utilization	%
F_{AO}	Molar Feed rate	$mols^{-1}$
H	Height of the Bioreactor	m
I_L	Vertical distance between adjacent stirrer blades	m
J_L	Length of the jacket	
K_m	Monods constant	$kmol/m^3$
k_d	Endogenous respiration coefficient or specific maintenance rate	(d^{-1})
m	Mass of dry solids	Kg
N_{A0}	Number of moles	mols/day
P_s	Percent solids expressed as decimal	
P_x	Net mass of cell tissue produced per day	kg/d
Q	Flow rate of methane	m^3/d
R	Gas constant,	kJ/kmol K
r_{fi}	Rate of reaction of component i	$mgl^{-1}s^{-1}$
S	Biological carbonaceous oxygen demand (BCOD) in the effluent biosolids	mg/l
SRT	Solids retention time	days
S_D	Side depth of Bioreactor	m
S_0	Biological carbonaceous oxygen demand (BCOD) in the influent Sludge	mg/l
t	Time	days
V_d	Volatile solids destroyed	%
V_R	Volume of Bioreactor	m^3
V_{RC}	Culture Volume	m^3
V(t)	Volumetric Feed rate at time t	m^3/d
$V_{CH_4,}$	Volume of methane produced	m^3/d
X_A	Conversion	
X_1	Biomas conentration	mg/l
$X_{1,0}$	Initial concentration of biomass	mg/l
X_2	Sludge conentration	mg/l
$X_{2,0}$	Initial concentration of Sludge	mg/l
Y	Yield coefficient given as mass of sludge or biomass produced per unit biosolids removed	
Ƶ	Depth of bed	m
$\frac{1}{\tau}$	Space velocity	hr^{-1}
θ_c	Mean cell residence time	days
μ_m	Maximum specific growth rate or half minimal velocity concentration	hr^{-1}
ρ	Density	kg/m^3
ρ_w	Specific weight of water	kg/m^3
τ	$space\ time$	hrs