International Journal Of Engineering Research And Development
e- ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 21, Issue 2 (February 2025), PP 45-57

Design of Continuous Stirred-Tank Reactor for Biogas Production from Cassava Wastewater Using Potassium Hydroxide Catalyst

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ABSTRACT
Cassava wastewater from cassava processing activities, if not properly disposed constitutes danger to humans and the environment.A laboratory investigation on anaerobic digestion of cassava wastewater for biogas production in a batch reactor was conducted. The batch experimental results were subjected to Monod kinetic model to determine the kinetic parameters used for the design of continuous stirred–tank reactor. Microbial maximum specific growth rate (μ_{max}) of 0.4236 day^{-1}) and half velocity constant (K_s) of 2077.9mg/cm^3 were evaluated for a hydraulic retention time of 30days at a mesophilic temperature of 35^{0}C. Mathematical models were developed for the design ofcontinuous stirred–tank reactor. The design models were simulated over a range of fractional conversion from 0.1 to 0.9 for volume, height, diameter, heat generated per unit volume of reactor, reactor heat exchanger dimension and capital cost of the reactor. It was found out that, the volume, height, diameter and capital cost of reactor increases exponentially with increasing fractional conversion. While the heat generated per unit volume of reactor and reactor heat exchanger dimension decreases linearly with increasing fractional conversion.

Keywords: *cassava wastewater, biogas, anaerobic digestion, continuous stirred -tank reactor,*

Date of Submission: 04-02-2025 Date of acceptance: 14-02-2025

I. INTRODUCTION

Cassava (Manihotesculenta, Cranntz) is a food crop grown in Nigeria and other tropical, Asian and Latin America countries. It is a tuberous crop cultivated worldwide for its high starch energy content for ruraldweller(Okunade&Adekalu, 2013). In the Southern part of Nigeria, cassava plays adorminant economic role among the rural populace where it is cultivated and processed into garri, fufu, starch and flakes, thus providing a source of income for the farmers (Izah et al., 2017). Recently, there is large scale processing of cassava root tubers into cassava flour, cassava flake, starch, garri, e.t.c. with less moisture content for domestic and industrial use (Mbongo&Antai, 1994). Much waste generated constitutes environmental nuisance, polluting the land, water and air. The scale of production and processing techniques are determining factors on the amount of cassava wastes generated. The processing of cassava begins with the removal of peels, fermentation or grating of the root tubers, followed by hydraulic pressing (dewatering). Identification has been made of three main sources of cassava wastewater which include water for washing cassava tubers after peeling, water from fermentation of cassava root tubers and extraction after grating (Ugwu&Agunwamba, 2012). Processing of cassava root tubers industrially into garri and starch by factories, generate a lot of wastewater whose discharged into the environment directly, leached into the soil, contaminates surface and underground water (Oladele, 2014). In areas where ditches are dug around cassava processing plant and subsequently channeledto an uncovered ponds become a threat to humans due to the unpleasant odour emanating from the ponds. Theopen ponds also serve as breeding ground for mosquitoes the carrier of malaria parasites (Djuma'ali et al., (2011). It has been reported that cassava wastewater is toxic and poisonous due to its acidity and cyanide content which is capable of stripping the soil bare of its vegetation and renders it unproductive (Izonfuo et al., 2013). The management and control ofenvironmentalpollution caused by cassava wastewater,result to biogas production using anaerobic digestion techniques by microorganisms in a batch reactor.

1.2: Phases of Anaerobic Digestion

Anaerobic digestion is a biochemical reaction whereby microorganisms such as bacteria break down organic matter in the absence of oxygen. Fourphases are involved in the anaerobic digestion of cassava wastewater (Yang et al., 2016). These phases are:

- Hydrolysis
- Acidogenesis
- Acetogenesis
- Methanogenesis

Phase 1: Hydrolysis

The hydrolysis of complex organic matter made up of carbohydrate, protein, fat and lipids occur by extra cellular enzymes. Water ionizes to release hydrogen ion (H^+) and hydroxyl ion (OH^-) during hydrolysis. Carbohydrates, proteins and fats are broken down into low molecular weight glucose, amino acids and fatty acids, which are subsequently acted upon by acidogenic bacteria

$H_2O_{(l)} \leftrightarrow H^+_{(aq)} + OH^-_{(aq)}$ (1)

hydrogen ion hydroxyl ion

$C_{12}H_{22}O_{11} + H_2O \rightarrow 2C_6H_{12}O_6$ (2)

carbohydrate glucose

Phase 2: Acidogenesis

The acidogenic bacteria convert low molecular weight glucose, amino acid and fatty acid into unstable intermediates(butyric acid, propionic acid and valeric acid) with the release of ammonia and hydrogen sulphide.

$C_6H_{12}O_6 \rightarrow C_3H_7COOH + 2CO_2 + 2H_2$ (3)

glucosebutyric acid

$C_6H_{12}O_6 + 2H_2 \rightarrow 2C_2H_5COOH + 2H_2O$ (4)

propionic acid

Phase 3:Acetogenesis

The acetogenic bacteria convert the intermediate products (butyric acid, propionic acid and valeric acid) to acetic acid or ethanol with release of hydrogen and carbon dioxide.

$C_3H_7COOH + 2H_2O \longrightarrow 2CH_3COOH + 2H_2$ (5)

acetic acid

$2C_2H_5COOH + 2H_2O \longrightarrow 3CH_3COOH + 2CO_2 + 3H_2$ (6)

Phase 4: Methanogenesis

This is the last stage of anaerobic digestion, resulting in the production of methane primarily from acetic acid or hydrogen and carbon dioxide by methanogenic bacteria. Since methane production is a slow process, it is generally regarded as the rate–limiting step of anaerobic digestion.

$CH_3COOH \longrightarrow CH_4 + CO_2$ (7)

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ (8)

methane

The general biochemical equation for anaerobic digestion by bacteria using organic matter as substrate is:

Organic matter + $H_2O \xrightarrow{anaerobes} CH_4 + CO_2 + NH_3 + H_2S$ + New cells + Heat (9)

1.3 Monod Kinetic Model

Monod kinetic model was applied in the investigation of anaerobic digestion of cassava wastewater inoculated with bacteria. The population of the microorganisms feeding on the cassava wastewater (substrate) could be represented as(X). The rate of microbial increase is proportion to the initial microbial concentration. The rate equation could be expressed as a first–order, as follows:

$r_x = \frac{d[X]}{dt} = \mu[X]$ (10)

Where $\frac{d[X]}{dt}$ – Microbial growth rate (mg/l/day)

[X] – Microbial concentration (mg/l)

μ – Microbial specific growth rate(day^{-1})

Re-arranging and integrating equation (10)gives:

$\ln [X_t] = \ln [X_0] + \mu t$ (11)

Where $[X_0]$ – Initial microbial concentration(mg/l)

$[X_t]$ – Microbial concentration attime t (mg/l)

Plotting a graph of $\ln [X_t]$against (t) gives a straight line with slope equal to (μ) and intercept equal to $\ln [X_o]$.

Microbial specific growth rate (μ) as a function of microbial concentration [X] and limiting substrate concentration [Ŝ] was identified by Monod (Reynolds and Richards, 1996). The empirical equation relating microbial specific growth rate and the limiting substrate concentration which is known as Monod equation is expressed as:

$$\mu = \mu_{max}\left(\frac{[\hat{S}]}{K_s+[\hat{S}]}\right) \quad (12)$$

Where μ_{max} – Microbial maximum specificgrowth rate (mg/l)
[Ŝ] – concentration of limiting substrate
K_s -half velocity constant (mg/l)
Substituting equation (12) into equation (10) gives:

$$r_x = \frac{d[X]}{dt} = \mu[X] = \mu_{max}\left(\frac{[\hat{S}]}{K_s+[\hat{S}]}\right)[X] \quad (13)$$

Equation (13) is the Monod kinetic model.
The additional assumptionwas,the rate of decrease in substrate concentration is proportional to the rate ofmicrobial increase. (Reynolds & Richards, 1996).

$$r_s = -\frac{d[\hat{S}]}{dt} = \frac{d[X]}{dt} = \mu_{max}\left(\frac{[\hat{S}]}{K_s+[\hat{S}]}\right)[X] \quad (14)$$

From equation (11), we have:

$$\mu = \frac{\ln[X_t] - \ln[X_0]}{t} \quad (15)$$

Recalling and linearizing equation (12), we have:

$$\mu = \mu_{max}\left(\frac{[\hat{S}]}{K_s+[\hat{S}]}\right)$$

$$\frac{1}{\mu} = \frac{K_s}{\mu_{max}[\hat{S}]} + \frac{1}{\mu_{max}} \quad (16)$$

Plotting a graph of $\frac{1}{\mu}$ against $\frac{1}{[\hat{S}]}$will give a straight line with slope equal to $\frac{K_s}{\mu_{max}}$ and intercept equal to $\frac{1}{\mu_{max}}$. From the intercept and slope, the values of μ_{max} and half saturation constant (K_s) can be evaluated.

II. MATERIALS AND METHODS

2.1 Materials

The materials used in this investigationare thermostat water bath, weighing balance, a 4litre improvised PVC batch reactor, thermometer, digital pH meter, pressure gauge, measuring cylinder, conical flask, pipette, burette, test tubes, NR8082 specie of sweet cassava, sodium hydroxide and potassium hydroxide catalyst.

2.2Methods

2.2.1 Feed Preparation

The NR8082 specie of sweet cassava root tubers was obtained from Federal Ministry of Agriculture, Port Harcourt, Nigeria. The cassava tubers were peeled, washed and grated in a cassava milling plant. The grated cassava was packed into knitted polyethene bag and dewatered. The wastewater extracted from the grated cassava root tubers constitutes the raw feed for the experiment. The pH of the cassava wastewater was measured immediately and allowed to settle for 24hours by gravity. It was decanted into a 20litre plastic container for experiment at Chemical Analysis Laboratory of Chemical/Petrochemical Engineering Department, Rivers State University, Port Harcourt.

2.2.2 Experiment for Production of Biogas from Anaerobic Digestion of Cassava Wastewater.

A laboratory scale experiment set up for the biogas production process in a batch reactor under isothermal condition, at a mesophilic temperature of 35^0C is shown in Figure 2.

Figure 2: Experimental Set-up for Biogas Production

A 3000cm^3 volume of cassava wastewater weighing 3644g with 5cm^3 of 0.1M aqueous potassium hydroxide catalyst was measured into a 4litre transparent (PVC) batch bio-reactor with a three – holes lid and inoculated with bacterial culture. One of the holes was fitted with mercury-in-glass thermometer and the other holes were fitted with a rubber hose connected to a pressure gauge and gas storage vessel for the biogas produced. The batch bioreactor was made air tight by application of glue and the headspace of the reactor was flushed with nitrogen gas, ensuring the status of anaerobic condition (Abubakar& Ismail, 2012). The pressure gauge had a referencepressure of 720mmHg. The plastic (PVC) batch reactor with its content under anaerobic condition was placedin a thermostat water bath set at a mesophilic temperature of 35^{0}C. The pressure on the gauge was read daily initiallyafter observation ofbiogasproduction and at 3days interval. Subsequent readings were made until the pressure drop became insignificant. The volume of biogas produced was estimated from the measured pressure reading using the van der Waal equation (Nelkon& Parker, 1984) expressed as:

$$(P + \frac{â}{V^2})(V - ɓ) = nR\ T \quad (17)$$

Where P – Absolute pressure (mmHg)
V – Volume of biogas produced (m^3)
n – Numbers of moles of biogas
â& ɓ - empirical constants
T– Experimental temperature (K)
R – Gas constant (62.364 L mmHg K^{-1}mol^{-1})
Note: Absolute pressure = Gauge pressure + Atmospheric pressure
The number of moles of biogas produced was obtained from the stoichiometric equation, stated as:

$$C_6H_{10}O_5 + H_2O \xrightarrow{\text{catalyst}} 3CH_4 + 3CO_2 \quad (18)$$

Starch water methane carbon dioxide

2.2.3 Experiment for Determining Cassava Wastewater (Substrate) Concentration

Thecassava wastewater (substrate)concentration was determined in relative to the hydrocyanic acid concentration by titration using phenophthalein as indicator. A set of eleven transparent plastic bottles of 350cm^3 capacity were filled with 250cm^3 cassava wastewater and 5 cm^3 of 0.1M aqueous potassium hydroxide catalyst. The samples were labeled S_0, S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8, S_9 and S_{10}. (Ugwu&Agunwamba, 2012). Sample S_0 was set aside for titration to determine the initial concentration of cassava wastewater, while the remaining ten samples were placed in the thermostat water bath set at a mesophilic temperature of 35^{0}C.

Figure 2: Experimental Set – up for Determining Cassava Wastewater (Substrate) Concentration

The concentration in each reactor was determined at 3days interval by titration with aqueous sodium hydroxide and phenophthalein as indicator. At end point, the phenolphthalein changes from purple to colourless and the volume of cassava wastewater used was read from the burette. The volume of cassava wastewater (substrate) at end point was used to determine the molar concentration of hydrocyanic acid (Ababio, 2002) using the formula expressed in equation (19)

$$\frac{C_A \times V_A}{C_B \times V_B} = \frac{A}{B} \quad (19)$$

Where C_A – Molarity of acid (M)
C_B – Molarity of base ((M)
V_A – Volume of acid (cm^3)
V_B – Volume of base (cm^3)
A – Mole ratio of acid
B – Mole ratio of base
The stoichiometry of the reaction is:

$$HCN_{(aq)} + NaOH_{(aq)} \rightarrow NaCN + H_2O \quad (20)$$

hydrocyanic acid + sodium hydroxide → sodium cyanide + water

2.2.4 Experiment for Determining Microbial Concentration

The serial dilution method using plate count agar was used to determine the microbial concentration (Ben-David & Davidson, 2014).1cm^3 of bacterial culture was added to a 9cm^3 of cassava wastewater to prepare a 10cm^3stock. A 5 – fold serial dilution was made with a sterile 1cm^3 pipette.
From the last dilution, a 0.1cm^3 was plated in duplicate unto agar plate, spread with a sterile bent glass rod and incubated for 18 to 24 hours at a mesophilic temperature of 35^0C.The bacterial colonies were counted and average value used in calculating the colony forming unit per cubic centimetre. The formula for calculating the colony forming units per cubic centimetre is:

$$cfu/cm^3 = \frac{(\text{number of colonies}) x (\text{dilution factor})}{\text{volume of cultured plate}} \quad (21)$$

Cell concentration measured in cfu/cm^3 can be converted to mg/cm^3 according to the relationship stated by Kim et al. (2012) as follows:
2.04×10^8cfu/cm^3 = 2.085 mg/cm^3

III. DEVELOPMENT OF DESIGN EQUATIONS

3.1Design Equation for Continuous Stirred-Tank Reactor Volume

The design of a continuous stirred-tank reactor (CSTR) begins by writing a material balance with respect to a reactant or product (Levenspiel, 1999). Applying the general material balance to cassava wastewater which is the substrate or reactant, we have:

Rate of – Rate of – Rate of = Rate of
inflowoutflowdisappearance accumulation (22)

$$F_{SO} - F_S - (-r_S)V = \left(\frac{dN_S}{dt}\right)$$

(23)Where F_{SO} – Input molar flow rate (mol/s)
F_S – Output molar flow rate (mol/s)
Simplifying and applying a steady state condition to equation (23), it becomes:

$$V = \left(\frac{F_{SO} - F_S}{-r_S}\right) \quad (24)$$

In terms of fractional conversion, we have: $V = \left(\frac{F_{SO}X_A}{-r_S}\right)$ (25)
Equation (25) is the design equation for the volume of a continuous stirred-tank reactor. From equation (14),

$$r_S = r_x$$

Substituting equation (13) into (25) gives:

$$V_{cr} = \frac{F_{SO}X_A}{\mu_{max}\left(\frac{[\hat{S}]}{K_S+[\hat{S}]}\right)[X]} \quad (26)$$

In terms of fractional conversion, equation (26) becomes:

$$V_{cr} = \frac{F_{SO}X_A[K_s + C_{so}(1-X_A)]}{\mu_{max}[C_{so}(1-X_A)][X]} \quad (27)$$

Equation (27) is the design equation for continuous stirred-tank reactor volume for anaerobic digestion of cassava wastewater operating under isothermal condition using Monod kinetic model.

3.2 Continuous StirredTank Reactor Dimensions and Configuration

Theconfiguration of reactors is described by the shape in relationship with its size parameters. The relationship between the volume of a cylindrical reactor, its length and diameter is stated as follows:

$V_{cr} = A_{cr} \times H_{cr}$ (28)
Where A_{cr} – Area of CSTR (m^2)
H_{cr} – Height of CSTR (m)
But

$$A_{cr} = \frac{\pi D^2_{cr}}{4} \quad (29)$$

$$V_{cr} = \frac{\pi D_{cr}^{\ 2}}{4} H_{cr} \quad (30)$$

$$H_{cr} = \frac{4V_{cr}}{\pi D_{cr}^{\ 2}} \quad (31)$$

Substituting equation (27)into equation (31) gives:

$$H_{cr} = 4\frac{F_{SO}X_A[K_s + C_{so}(1-X_A)]}{\mu_{max}[C_{so}(1-X_A)][X]}\left[\pi D_{cr}^{\ 2-1}\right] \quad (32)$$

The Height to diameter ratio of a continuous stirred-tank reactor is 3:2 (Hysys Operations Guide, 2011) expressed as:

$$\frac{H_{cr}}{D_{cr}} = \frac{3}{2} \quad (33)$$

$$D_{cr} = \frac{2}{3}H_{cr} \quad (34)$$

Substituting equation (34) into equation (32)and simplifying itgives:

$$H_{cr}^{\ 3} = \frac{9F_{SO}X_A[K_s + C_{so}(1-X_A)]}{\mu_{max}[C_{so}(1-X_A)][X]\pi} \quad (35)$$

$$H_{cr} = \left[\frac{9F_{SO}X_A[K_s + C_{so}(1-X_A)]}{\mu_{max}[C_{so}(1-X_A)][X]\pi}\right]^{1/3} \quad (36)$$

From equation (34), the diameter of CSTR is given as:

$$D_{cr} = \frac{2}{3} * \left[\frac{9F_{SO}X_A[K_s + C_{so}(1-X_A)]_{1/3}}{\mu_{max}[C_{so}(1-X_A)][X]\pi}\right] \quad (37)$$

3.3 Heat Generated per Unit Volume of Continuous Stirred-Tank Reactor

The heat generated per unit volume of continuous stirred–tank reactor due to anaerobic digestion of organic waste according to Abowei and Ogoni (1990) could be expressed as follows:

$$q = \frac{(\Delta H_r)F_{SO}X_A}{V_{cr}} \quad (38)$$

Substituting equation (27) into equation (38) gives:

$$q = \Delta H_r F_{SO}X_A\left[\frac{F_{SO}X_A[K_s + C_{so}(1-X_A)]_{-1}}{\mu_{max}[C_{so}(1-X_A)][X]}\right] \quad (39)$$

3.4 Heat Exchanger Dimension for Continuous Stirred-Tank Reactor

The heat transfer from the heating coil to the reactor according to Abowei (1989) is given as:

$$q = UA\Delta T \quad (40)$$

Where U – Heat transfer coefficient (J/m^2s^0C)

A – Surface area for heat exchanger (m^2)

ΔT – Temperature difference between water and reactor (^0C)

$$U = \frac{q}{A\Delta T} \quad (41)$$

Substituting equation (39) into equation(41) gives:

$$U = \frac{(\Delta H_r)\,\mu_{max}\,[C_{so}(1-X_A)][X]}{[K_s + C_{so}(1-X_A)]A\Delta T} \quad (42)$$

The heat transfer surface area is given as:

$$A = 2\pi\, r l_c \quad (43)$$

Where l_c – Length of heating coil (m)

r – Radius of heating coil (m)

Substituting equation (43) into equation (41), gives:

$$U = \frac{(\Delta H_r)\,\mu_{max}\,[C_{so}(1-X_A)][X]}{[K_s + C_{so}(1-X_A)]2\pi\, r l_c} \quad (44)$$

3.5 Cost of Continuous Stirred-Tank Reactor

The capital cost of reactor expressed by Coulson & Richardson (2005) is stated as:

$$C_T = C_R\left(\frac{I_p}{I_R}\right)\left(\frac{V_p}{V_R}\right)^f \quad (45)$$

Where C_T – Proposed cost of current reactor ($)

C_R – Current cost of already existing reactor at the base year ($)

V_p – Volume of current reactor (m^3)

V_R – Volume of already existing reactor (m^3)

f – index factor

I_P – Cost index of proposed reactor atcurrent year

I_R – Cost index of already existing reactor at the base year

Exchange rate 1US dollar = ₦1500:00 (Nigeria's currency).

For a continuous stirred–tank reactor, the capital cost is expressed as:

$$C_{Tcr} = C_R\left(\frac{I_p}{I_R}\right)\left(\frac{V_{cr}}{V_R}\right)^f \quad (46)$$

Substituting equation(27) into equation (46) gives:

$$C_{Tcr} = C_R\left(\frac{I_p}{I_R}\right)\left\{\frac{F_{so}X_A[K_s + C_{so}(1-X_A)]}{\mu_{max}\,[C_{so}(1-X_A)][X]} * \frac{1}{V_R}f\right\} \quad (47)$$

An algorithm was developed for the design equations, followed by writing a computer program using MATLAB R2015 and simulatedover a range of fractional conversion from 0.1 to o.9.

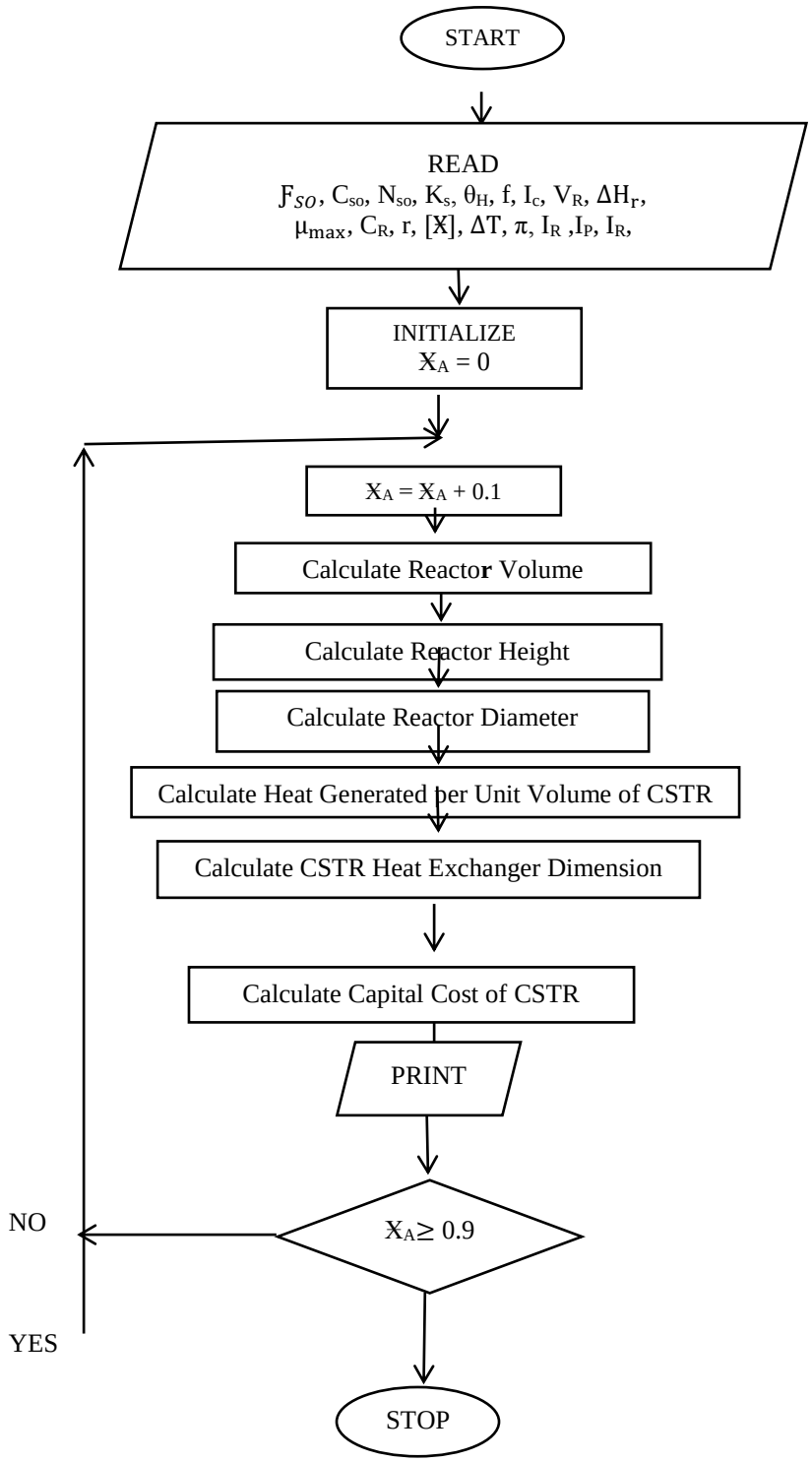

Figure 3: Flowchart for Continuous Stirred-Tank Reactor Design

IV. RESULTS

4.1 Evaluation of Kinetic Parameters

The Monod kinetic model was validatedby subjecting the batchexperimental resultsof anaerobic digestion of cassava wastewater under isothermal condition to the appropriate rate equation to obtain the kinetic parametersfor the design of continuous stirred–tank reactor.

Table 1: Experimental results and process kinetic parameters determination

Sample	θ_H (days)	$[\hat{S}_0]$ (mg/l)	$[\hat{S}_t]$ (mg/l)	$[X_0]$ (mg/l)	$[X_t]$ (mg/l)	$\frac{1}{[\hat{S}_t]}$	$\ln[X_0]$	$\ln[X_t]$	μ	$\frac{1}{\mu}$
S_0	0	2192.4	-	1.584	-	-	0.4599	-	-	-
S_1	3	2192.4	1722.**6**	1.584	18.70	0.000581	0.4599	2.9285	0.8229	1.2152
S_2	6	2192.4	1487.7	1.584	50.08	0.000672	0.4599	3.9136	0.5756	1.7373
S_3	9	2192.4	1289.8	1.584	134.09	0.000775	0.4599	4.8985	0.4932	2.0276
S_4	12	2192.4	961.5	1.584	286.70	0.001040	0.4599	5.6554	0.4332	2.3084
S_5	15	2192.4	881.0	1.584	439.50	0.001135	0.4599	6.0856	0.3751	2.6659
S_6	18	2192.4	768.4	1.584	408.70	0.001301	0.4599	6.0132	0.3085	3.2415
S_7	21	2192.4	691.2	1.584	358.60	0.001447	0.4599	5.8822	0.2582	3.8730
S_8	24	2192.4	598.3	1.584	162.50	0.001671	0.4599	5.0907	0.1929	5.1840
S_9	27	2192.4	505.8	1.584	98.30	0.001973	0.4599	4.5880	0.1529	6.5402
S_{10}	30	2192.4	425.5	1.584	23.59	0.002350	0.4599	3.1608	0.0900	11.111

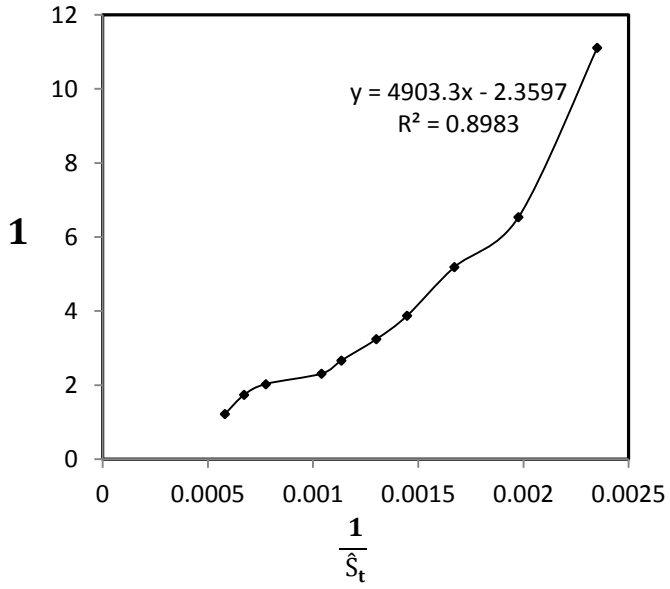

Figure 4: Determination of Microbial Maximum Specific Growth Rate and Half Velocity Constant for Catalytic Anaerobic Digestion of Cassava Wastewater

Figure 4 is a variation of $\frac{1}{\mu}$ with $\frac{1}{\hat{S}_t}$ for catalytic anaerobic digestion of cassava wastewater with gradient equal to $\frac{K_S}{\mu_{max}}$ and intercept equal to $\frac{1}{\mu_{max}}$.The model describing the microbial specific growth rate is expressed in equation (48) with a coefficient of regression ($R^2 = 0.8983$).

$$\frac{1}{\mu} = 4903.3\frac{1}{\hat{S}_t} - 2.3597 \quad (48)$$

4.2 Reactor Design and Simulation

The design equations for continuous stirred-tank reactor were simulated over a range of fractional conversion (X_A) from 0.1 to 0.9 using MATLAB R2015, a computer aided program. The parameters simulated are volume, height, diameter, heat generated per unit volume of reactor, reactor heat exchanger dimension and cost of reactor using their appropriate kinetic models.

Table 2: Simulation results forcontinuous stirred–tank reactor

X_A	V_{cr} (m^3)	H_{cr}(m)	D_{cr} (m)	q (J/m^3)	U (J/s^0Cm)	CT_{cr}(₦) Million
0.1	9.4994	3.0045	2.0010	4.7717	20.249	11.4514

X_A	V_{cr} (m^3)	H_{cr}(m)	D_{cr} (m)	q (J/m^3)	U (J/s^0Cm)	CT_{cr}(₦) Million
0.2	21.2969	3.9312	2.6182	4.2568	18.064	15.8164
0.3	36.3774	4.6984	3.1291	3.7382	15.863	19.5936
0.4	56.3825	5.4366	3.6208	3.2158	13.646	23.3474
0.5	84.2670	6.2149	4.1392	2.6896	11.413	27.4185
0.6	125.9403	7.1047	4.7318	2.1595	9.1641	32.1993
0.7	195.1912	8.2208	5.4751	1.6256	6.8983	38.3676
0.8	333.3864	9.8251	6.5435	1.0877	4.6158	47.5291
0.9	747.3578	12.8552	8.5616	0.5459	2.3164	65.6435

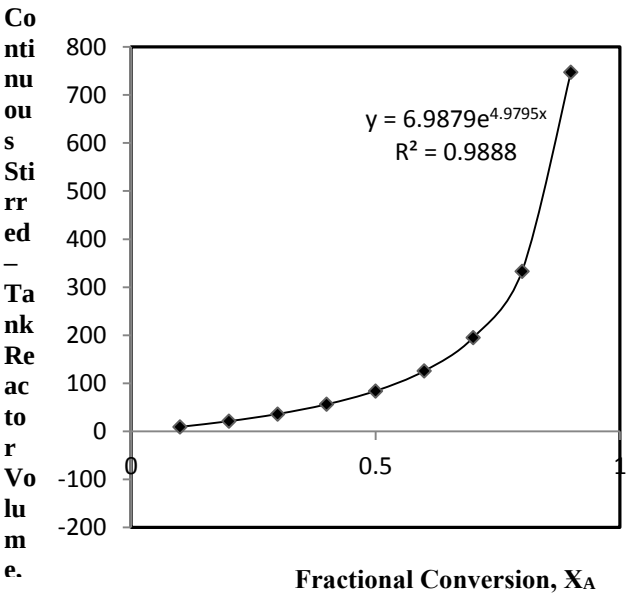

Figure 5: Variation of Continuous Stirred-Tank Reactor Volume with Fractional Conversion

Figure 5 shows the variation of continuous stirred–tank reactor volume with fractional conversion for catalytic anaerobic digestion of cassava wastewater. TheCSTR volume increases exponentially with arithmetic increase in fractional conversion, depicted by a curve described by equation (49):

$V_{cr} = 6.9879e^{4.9795X_A}$ (49)

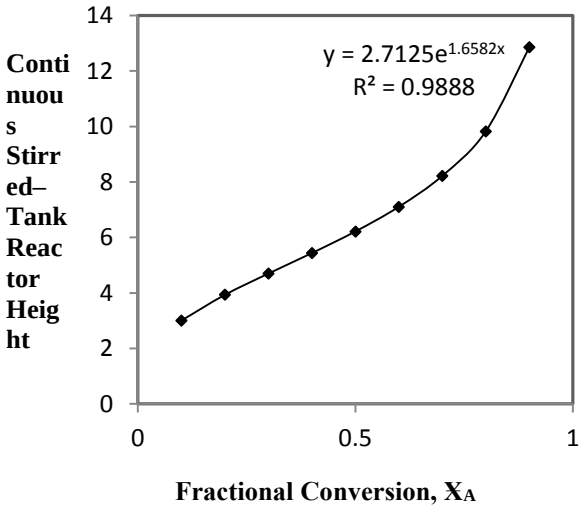

Figure 6: Variation of Continuous Stirred-Tank Reactor Height withFractional Conversion

Figure 6 shows the variation of continuous stirred–tank reactor height with fractional conversion for catalytic anaerobic digestion of cassava wastewater. The continuous stirred–tank reactor height increasesexponentially with increasing fractional conversionwith a curve, described by:

$H_{Cr} = 2.7125e^{1.6582\ X_A}$ (50)

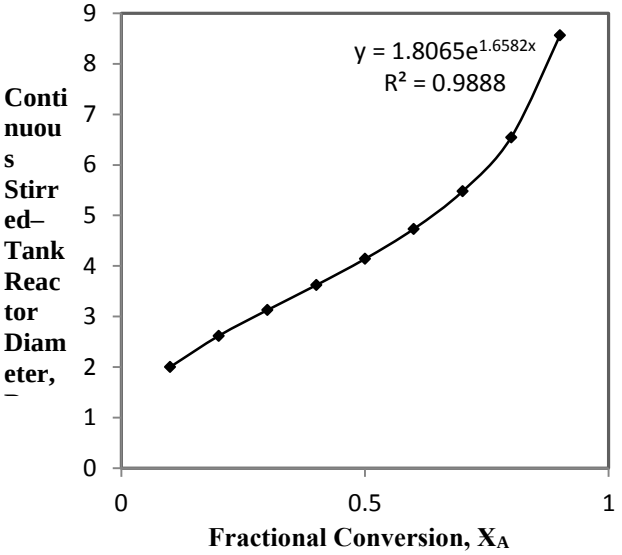

Figure 7: Variarion of Continuous Stirred-Tank Reactor Diameter with Fractional Conversion

Figure 7 shows the variation of continuous stirred–tank reactor diameter with fractional conversion for catalytic anaerobic digestion of cassava wastewater. The continuous stirred–tank reactor diameter increases exponentially with increasing fractional conversion with a curve, described by equation (51) below:

$D_{br} = 1.8065e^{1.6582\ X_A}$ (51)

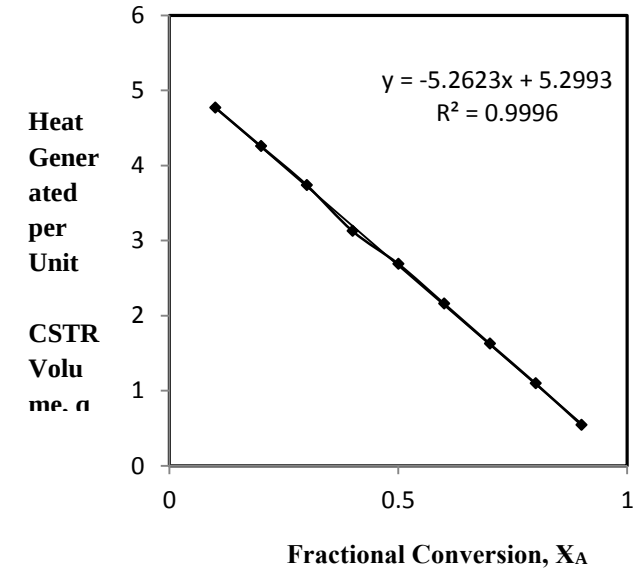

Figure 8: Variation of Heat Generated per Unit Volume of Continuous Stirred-Tank ReactorwithFractional Conversion

Figure 8: shows the variation of heat generated per unit volume of continuous stirred–tank reactor with fractional conversion. There is a decrease in heat generated per unit volume of CSTR with increasing fractional conversion, described by equation (52) below:

$q = -5.2623\ X_A + 5.2993$ (52)

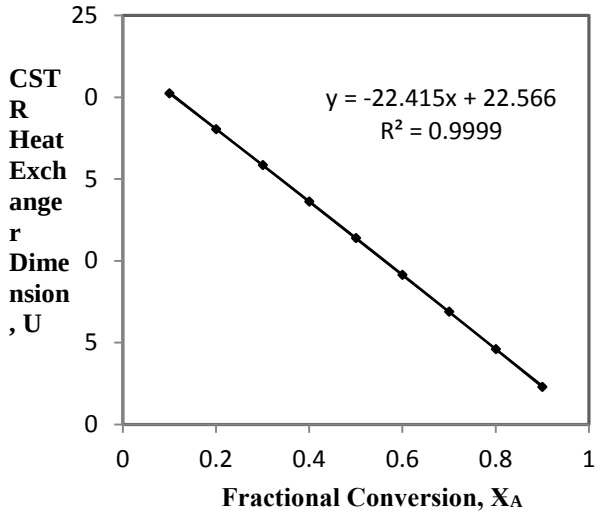

Figure 9: Variation of Continuous Stirred-Tank Reactor Heat Exchanger Dimension withFractional Conversion

Figure 9 shows the variation of continuous stirred –tank reactor heat exchanger dimension with fractional conversion. There is a decrease in CSTR heat exchanger dimension with increasing fractional conversion expressed by equation (53).

$U = -22.415\ X_A + 22.566$ (53)

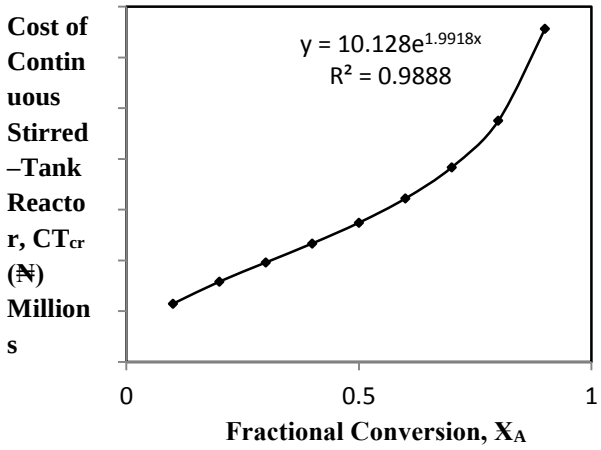

Figure 10: Variation of Cost of Continuous Stirred–Tank Reactor with Fractional Conversion

Figure 10 shows the variation of cost of continuous stirred–tank reactor with fractional conversion. It depicts an exponential increase in cost of continuous stirred–tank reactor with increasing fractional conversion, expressed by equation (54).

$CT_{cr} = 10.128e^{1.9918\ XA}$ (54)

V.DISCUSSIONANDCONCLUSION

The indiscriminate disposal of cassava wastewater poses an environment problem which could be managed and controlled by anaerobic digestion in a reactor. A laboratory scale anaerobic digestion of cassava wastewater for biogas production using potassium hydroxide (KOH) catalyst was performed in a batch reactor. The batch experimental results were subjected to Monod kinetic model for the determination of microbial maximum specific growth rate (μ_{max})of 0.4236 day^{-1}) and half velocity constant (K_s) of 2077.9mg/cm^3were used in the design of continuous stirred–tank reactor. Design equations were developed along with their algorithm and a computer program was written for solving the design equations using MATLAB R2015. Design parameters such as volume, height,diameter, heat generated per unit volume of reactor, reactor heat exchanger dimension and capital cost of the continuous stirred–tank reactor were simulated over a range of fractional

conversion from 0.1 to 0.9.The simulated results show that the volume, height, diameter and cost of thecontinuous stirred–tank reactorincreased exponentially with fractional conversion. While the heat generated per unit volume of reactor and heat exchanger dimension decreased linearly with fractional conversion. The models developed in this piece of work would ease the design and fabrication of various sizes of continuous stirred–tank reactorsfor biogas production, in addition to solving the environmental pollution caused by cassava processing activities and provide alternate source of energy.

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