Design of Cow-Dung and Grass- Clippings Isothermal Continuous Stirred Co-digester for biogas production

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ABSTRACT

The continuous search in renewable energy sources for industrial and domestic utilization is very imperative and motivated this study. The study of Cow- dung and grass clippings Co-digestion are important due to the fact that the successful outcome of the studies will provide a basis for waste minimization and enhance renewable energy production for global consumption. This work, therefore, is focused by exploiting the modified Gompertz kinetic equation in developing design models for the simulation of continuously stirred co-digester (CSC) at the isothermal condition. Co-digester functional dimensions such as volume, length, space-time, space velocity and heat generation per unit volume were developed for Continuous Stirred Co-digester type..The developed models were simulated using Matlab codes programming technique using the design basis of 50,000 metric tons of biogas per annum at 370 C isothermal condition. The developed performance models were solved numerically using MATLAB version 7.1 within the operational limit of conversion degree, XA = 0.1 to 0.9. The results obtained showed that the increase in fractional dimensions of Co-digester volume VR, length LR, and Spacetime SV- increases with an increase in fractional conversion at a constant radius. Results of space velocity (SV-) and heat generation/per unit volume (q) showed inverse characteristic behavior as an increase in fractional conversion decreases space velocity and heat generation per unit volumes.. Further careful examination of the results, demonstrated that at an optimal yield of 0.9 degrees of conversion, Co-digester volume value of 10.0m3 at constant radius was feasible. The results as obtained in this work proved a dependable relationship with the fractional conversion.

Key Words: Design, Isothermal, Grass-clipping, Cow-dung Continuous Stirred, Co-digester, Gompertz rate Equation.
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1. INTRODUCTION

Researchers globally have resolved in tackling the high potential of global warming problems resulting from the utilization of non-renewable energy sources for industrial and domestic use. These have led to increased awareness search (Angelidaki, 1996; Angelidaki et al, 2003; Igoni et al, 2008; Abdulsalam & Yusuf, 2015; Igoni & Harry, 2017) for alternative renewable energy sources, such as biogas and bio-fuels production; that expected to elevate global economy and minimize global warming problems. In addition, the significance of this study will also encompass the following; (Angelidaki 1996). It will reduce the environmental nuisance of cow-dung and grass clippings waste contamination problems (Abowei & Goodhead 2014). The CH_4 gas produced will be useful for both industrial and domestic application (Igoni et al 2008). The digester models to be developed in this work will be generalized and can be applied with a known kinetic model to simulate the functional dimensions of any digester type.

 To this end, it is necessary to research on the possibilities of developing various Co-digester types in the treatment and production of bio-gas using all domestic and industrial wastes routes. Major expected achievable deliverables in this waste recycling process are waste minimization, renewable product formation, boost global economy and of course enhances employment capacity. Hence, this research is a prelude to the adoption of modified Gompertz rate equation sighted in (Anthony et al, 2015) works of Cow-Dung and Grass Clipping combination as raw materials for renewable energy sources.

In order to establish the design models with respect to the Isothermal continuous stirred co-digester unit, it is relevant to appraise quantitatively and qualitatively the scientific aspect of cow-dung and grass-clippings as related to properties, structure, and reaction mechanisms. Interestingly, cow-dung and grass-clippings are readily available materials that can be used to produce bio-gas through the biodegradability in a co-digester process.

1.2 Cow-Dung Properties and Structure

Colour: **black**

Density = $22kg/m^3$

The chemical structure of Cow dung is mainly the combination of Ammonium carbonate hydroxide and cellulose and small proportion of Phosphate, Potassium and calcium. Thus;

$(NH_4)_2 \, CO_3 \, OH +$

Cellobiose unit
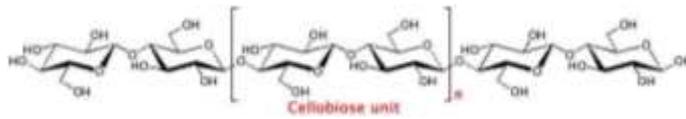
$\Rightarrow$ Cow Dung

Ammonium Carbonate Hydroxide

Grass-Clippings Properties and Structure

Typical Grass Clipping processes

The following physical characteristics are identified with grass clipping;

Colour: Green

Density = $91 – 227.445kg/m^3$ (Garden Grass)
                   150 – 450 for Garden Trees

Structure of Grass Clipping

1.   **a-D-Glucose**

2.   **Starch**

lycosidic linkage

α-1, 4-glycosidic linkages
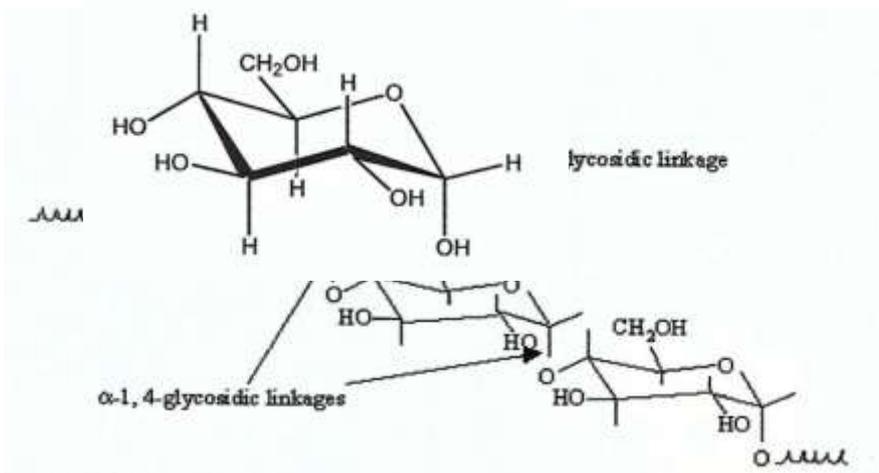
3.   **Cellulose**
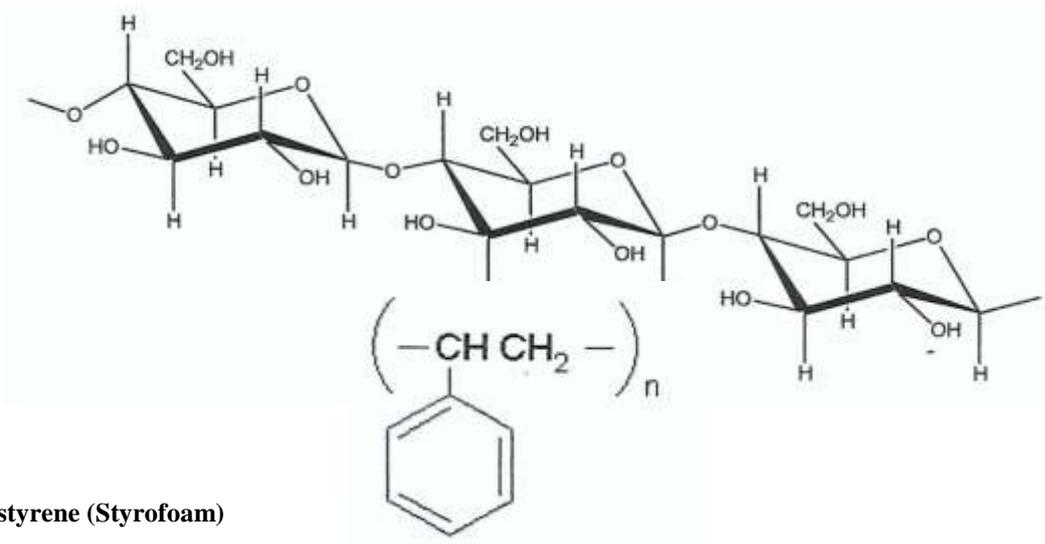
1. **4.Polystyrene (Styrofoam)**

Properties and structure of Biogas (CH$_4$)

It physical properties includes;

Density   =   1.5kg/m^2

Viscosity   =   1.13kg/s.m

Moisture Content =   50 – 70%

Stoichiometry of Grass Clippings and Cow-Dung Reaction

The possible stoichiometric equation describing grass clipping cow-dung reaction is invoked using induction principles of reaction mechanism and proposed as;

$$Cow\text{-}dung + cellulose \Rightarrow Methanogenesis$$

$(NH_4)_2\ CO_3\ OH$ +   +

$\Rightarrow$ $(NH_4)_2\ CO_3\ OH$
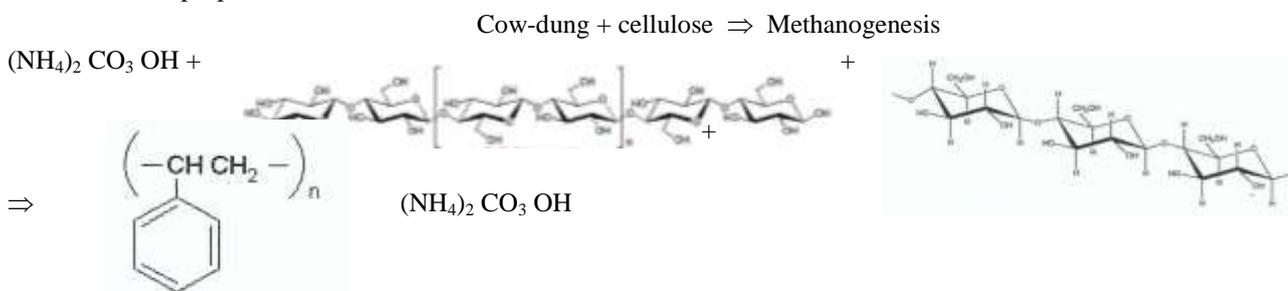
2.0 KINETIC RATE ANALYSIS

Numerous kinetic rate analysis were been postulated regarding bio-gas production from various municipal and industrial waste types. Matheri *et al.,* (2017) worked on optimizing biogas production from anaerobic co-digestion of chicken manure and organic fraction of municipal solid waste. In this work, the use of biochemical methane potential with 4:1 ratio with optimal biodegradation rates gave optimum biogas (methane) yield with 15 days retention time. Since it was an experimental research work, the materials were sourced locally and then subjected to laboratory investigation for results and discussions. The methanogenesis of the process gave CO_2 and biogas (CH$_4$) i.e. Glucose $\xrightarrow{\Delta} CO_2 + methane.$

Their findings gave reasonable amount of moisture content at 37^{0}C and pH 7 which after Buswell formula was used to determine the percentage of methane gave 40 – 70% (CH$_4$) and 30 – 60% (CO$_2$) and other traces of other elements. Thus, their work gave optimum biogas and methane yield at ratio of 1:1 but optimum biogdegradability is at 4:1 ratio.

Abdulsalam and Yusuf (2015) investigated the kinetic of biogas produced from cow and elephant dungs using residual substrate concentration approach. In the batch bio-digester, anaerobically the best biogas production of 3.92 x 10^{-4}g/cm^3 and average yield of 0.0845 over a period of 33 days follow a kinetic shifting order of (0 − 1). Also, the co-digestion of elephant and cow-dung of equal proportion can increase the yield of biogas.

Sreekrishnan (2004) researched on the design models for Anaerobic Batch Digesters producing Biogas from municipal solid waste. The use of Microsoft Visual Basic version 6.0 computer programme with fractional conversion range of $0.2 \leq \alpha \leq 0.8$ to get empirical optimum yield of 20% in the batch digester. A lot of literatures reviews were carried out on waste management in

Port Harcourt. Their materials were 5 batch-wise anaerobic digester of 5 litres for the experimental set-up. The digesters were the loaded with 2kg of organic municipal solid waste which was diluted to 26.7% total solids concentration and end up with the usual Monod rate equation.In addition, other researchers also limited their works to the laboratory analysis of possible methane production resulting to the use of Monod rate equation (Lastella et al 2002; Latinwo & Agarry 2015; Matheri 2015, 2016 & 2017)

$$\mu = \mu_{max} \frac{[S]}{K_s + [S]}$$

(1)

Where;

μ_{max} =   Maximum growth rate, day^{-1}

$[S]$ =   Concentration of limiting substrate, mg/L

K_s =   Half-saturation constant (i.e. concentration of S when $\mu = \frac{\mu_{max}}{2}$),

mg/L

$$\mu_{net} = \mu_{max} \frac{[S]}{K_s + [S]} [X] - k_d [X]$$

(2)

Where;

k_d =   Decay constant, day^{-1}

2.1 Modified Gompertz Kinetic Expression

Interestingly, Etuwe, C.N., *et al* (2016) worked on the development of mathematical models and application of the modified Gompertz model for Designing Batch Biogas Reactors. They got yield optimal (y_t) of 60 – 80g.VS/L at 42 days period. Comparatively, the modified Gompertz formula gave minimum time (λ) of 9.7 – 12 days and maximum yield (y_m) of 68 and 86ml/g at operating temperature of 37^0C and pH of 7.

Further work was reported on the kinetic of biogas rate from cow dung and grass clippings resulting to biogas production on a laboratory scale level.(Matheri etal 2015; Anthony et al 2015). Their works resulted in the development of a concise modified rate expression as follows:
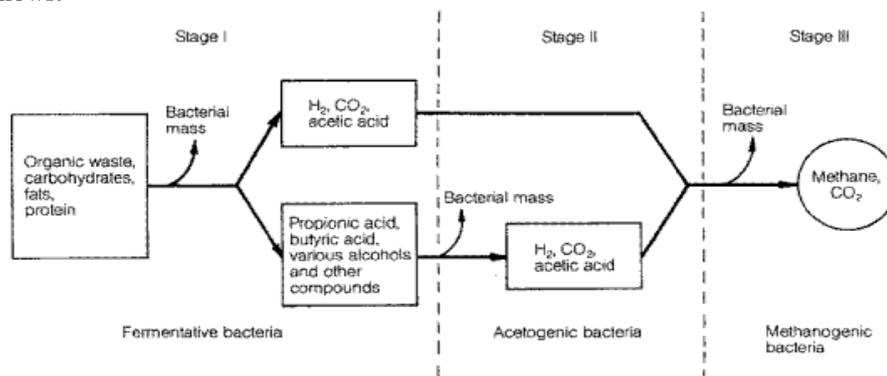
Fig. 1 Hypothetical Methanogenic process

Gompertz (Pesta 2007; Ostream 2004; Anthony 2015; Etuwe et al 2016) Considered a Pseudo – first order reaction process for the decomposition of cow-dung to CO_2 and CH_4 for the methonogenic bacteria process as shown below:

$$C_6H_{12}O_{6(L)} \xrightarrow{K} 3CO_{2(g)} + 3CH_{4(g)}$$

(3)

The rate expression for the methanogenesis process gives;

$$\left.\begin{array}{l}(-r_A) \alpha\ C_A^n \\ (-r_A) =\ KC_A^n \end{array}\right\}$$

(4)

Since it is a Pseudo – first order reaction, n = 1 hence, equation (50) becomes;

$$(-r_A) = \frac{-dC_A}{dt} = KC_A$$

(5)

In terms of fractional conversion, X_A

$$(-r_A) = k\ C_{Ao}(1 - X_A) \tag{6}$$

Where;

    k   =   Rate constant which is a function of time and it represent pre-exponential factor (A) in the modified Gompertz equation as;

    $(-r_A)$ =   Depleting rate of reactant and it is represented in the modified Gompertz equation as $Y(t)$

$$(-r_A) = Y(t) = A\exp\left[-\exp\left(\frac{\mu e}{A}(\lambda - t) + 1\right)\right]C_{Ao}(1 - X_A) \tag{7}$$

Equation (53) represent the rate law used for bio-gas production which will be exploited for the design of the continuous stirred co-digester.

Where;

    A   =   Biogas production potential
    Y   =   k(t) = cumulative of specific biogas production
    μ =   Maximum biogas production rate (d^{-1})
    e =   Mathematical constant (2.718282)
    t   =   Cumulative time for biogas production (days)
    λ =   Lag-phase period
    C_{AO} =   Initial concentration of the glucose; mol/L
    X_A =   Fractional conversion of converted reactant to product

Since the works reviewed used batch wise laboratory scale method to establish the Gompertz rate equation, it is worthwhile to adopt the modified rate equation to establish large scale design for various co-digester types. Therefore this work is focused on the application of Gompertz modified rate equation to design a Isothermal Continuous Stirred Co-digester (CSC) for bio-gas production using cow-dung and grass-clipping as raw materials.

3.0 MATERIALS AND METHODS

3.1 Materials

The materials exploited in this work encompassed mainly desk top research component such as; Laptop, Mathlab software, work spreadsheet and other associated computational tools for the simulation of the developed models below.

3.2 Development of Design Models

Applying simple material balance equation (Perry & Green 2008) is utilized for the development of the modeling equation thus; Input = output + Rate of disappearance + Accumulation. In this work consideration is based on the fact that flow is in steady state at isothermal condition with inform stirring and negligible pressure drop within the within the co-digester system, then;

3.3 Co-Digester Volume Model

Consider the schematic representation of a hypothetical continuous stirred co-digester with feeds and product as shown below.
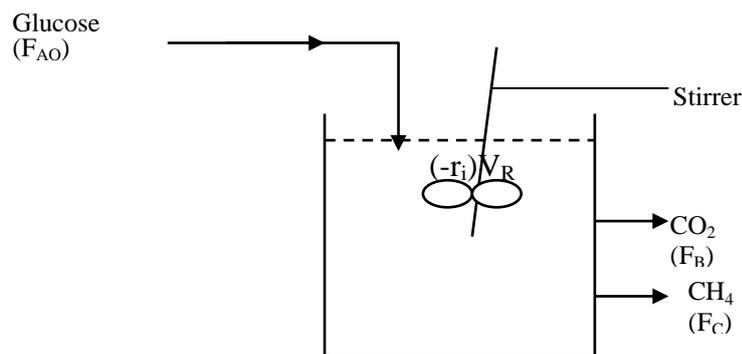
Figure 2: Hypothetical Continuous Stirred Co-digester

Input   = $F_A = F_{AO}\left(1 - X_{Ao}\right) = F_{AO}$

Output   = $F_{Af}\ =\ F_{AO}\left(1 - X_A\right) = F_{AO} - F_{AO}X_A$ (8)

Rate of disappearance = $-r_A V_R$

Accumulation   = $\dfrac{d}{dt}\left(C_A V_R\right) = 0$ (9)

Combining equation (8) to (9) yields

$$\frac{d}{dt}\left(C_A V_R\right)\ =\ F_{AO}\ -\ \left[F_{AO}\left(1 - X_A\right)\right]\ -\ \left(-r_A\right)V_R \tag{10}$$

At steady state, the accumulation term is equal to zero, i.e.

$$\frac{d}{dt}\left(C_A V_R\right)\ =\ 0$$
$$\therefore\ \ 0 = F_{AO}\ -\ \left[F_{AO}\left(1 - X_A\right)\right] - \left(-r_A\right)V_R \tag{11}$$

Expanding the bracket and simplifying;

$$0 = F_{AO}\ -\ F_{AO}\ +\ F_{AO}X_A\ -\ \left(-r_A\right)V_R$$
$$0 = F_{AO}X_A\ -\ \left(-r_A\right)V_R$$
$$V_R\ =\ \frac{F_{AO}X_A}{\left(-r_A\right)} \tag{12}$$

Substituting equation (12) into equation (7) yields the generalized model, thus;

$$V_R\ =\ \frac{F_{AO}X_A}{A\exp\left[-\exp\left(\dfrac{\mu e}{A}(\lambda - t) + 1\right)\right]C_{Ao}\left(1 - X_A\right)} \tag{13}$$

Co-digester Length (L$_R$) Model

Since the reactor is cylindrical, volume of a cylindrical reactor is given as

$$V_R\ =\ \pi R^2 L_R \tag{14}$$

Where:

V$_R$	=	Volume of reactor (m^3)
R	=	Radius of reactor (m)
L$_R$	=	Length of reactor (m)
π	=	Constant

Comparing equations (13) into (14) yields,

$$L_R\ =\ \left[\frac{F_{AO}X_A}{2\pi r^2.A\exp\left[-\exp\left(\dfrac{\mu e}{A}(\lambda - t) + 1\right)\right]C_{Ao}\left(1 - X_A\right)}\right]^{1/3} \tag{15}$$

Co-digester Space Time (τ_{CSTR}) Model

This is defined as the ratio of reactor volume to volumetric flow rate. thus

$$\tau_{CSTR} \quad = \quad \frac{V_R}{v_O} \tag{16}$$

Substituting equation (13) into (16) yields

$$\tau_{CSTR} \quad = \quad \frac{\dfrac{F_{AO} X_A}{A \exp\left[-\exp\left(\dfrac{\mu e}{A}(\lambda - t) + 1\right)\right] C_{Ao}(1 - X_A)}}{v_O} \tag{17}$$

$$F_{AO} \quad = \quad C_{AO} v_O \tag{18}$$

Substituting equation (18) into (17) yields,

$$\tau_{CSTR} \quad = \quad \frac{X_A}{A \exp\left[-\exp\left(\dfrac{\mu e}{A}(\lambda - t) + 1\right)\right] C_{Ao}(1 - X_A)} \tag{19}$$

Co-digester Space Velocity (S_V)

This is defined as the reciprocal of space time and mathematically modeled as.

$$S_V \quad = \quad \frac{1}{\tau_{CSTR}} \tag{20}$$

Substituting equation (19) into (20) yields

$$S_V \quad = \quad \frac{A \exp\left[-\exp\left(\dfrac{\mu e}{A}(\lambda - t) + 1\right)\right] C_{Ao}(1 - X_A)}{X_A} \tag{21}$$

Co-digester Heat Generated Per Unit Volume

Exploiting the works Abowei and Goodhead (2014), heat generation per unit volume model is derived as;

$$Q \quad = \quad \Delta H_R \, F_{AO} X_A \tag{22}$$

Q = Quantity of Heat (j/s)

ΔH_R = Heat of reaction (KJ/mol)

F_{AO} = Flow Rate of Species (mol/s)

X_A = Fractional Conversion of Species

Dividing through by V_R

$$\frac{Q}{V_R} = q = \frac{\Delta H_R \, F_{AO} X_i}{V_R} \tag{23}$$

$$q = \frac{\Delta H_R \, F_{AO} X_A}{V_R} \tag{24}$$

Where q = quantity of heat generated per unit volume of the co-digester

Combining Equations 24 and 13 results in;

$$q = \frac{\Delta H_R \, F_{AO} X_A}{\dfrac{F_{AO} X_A}{A \exp\left[-\exp\left(\dfrac{\mu e}{A}(\lambda - t) + 1\right)\right] C_{Ao}(1 - X_A)}} \tag{25}$$

Equation 25 can be simplified as;

$$q = \frac{\Delta H_R}{\left(A\exp\left[-\exp\left(\frac{\mu e}{A}(\lambda - t)+1\right)\right]C_{Ao}\left(1 - X_A\right)\right)^{-1}}$$

(26)

4.0   Computational Methods for Co-digester Design Parameters.
4.1   Stoichiometric mole computations

The essential operating design parameters for the simulation process were computed from the summarized stoichiometric equation. Thus;

$$\left(-CH\,CH_2-\right)_n (NH_4)_2\,CO_3\,OH \rightarrow [(CN)_2] + C_6H_{12}O_{6(L)} \xrightarrow{K} 3CO_{2(g)} + 3CH_{4(g)}$$

(87)

Methanogenesis   Anerarobic Degradation Factor
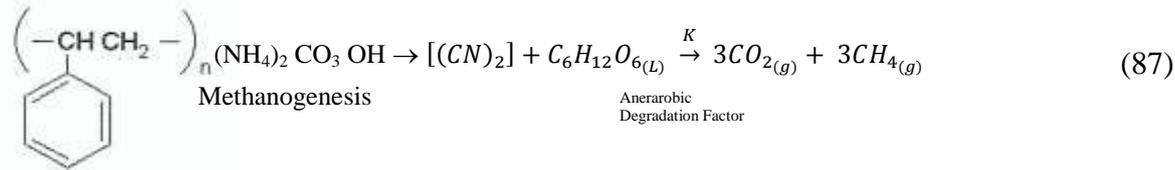
Table 1: Operating Parameters Determination.

S/No	Parameters	References
1.	Rate Constant Y (t)	Anthony, *et al.,* 2015
2.	$C_{AO} = 0.039\,mol/m^3$	Calculated
3.	$F_{AO} = 0.00019\,mol/s$	Calculated
4.	$V_O = 0.0047\,m^3/s$	Calculated
5.	$(-\Delta H_R) = 257\,KJ/mol$	Perry *et al.,* 2008
6.	Design Stress, $f = 130N/mm^2$	Sinnott, *et al.,* 2009
7.	Corrosion Allowance e = 1.25mm	Sinnott, *et al.,* 2009
8.	Design Pressure P_i = 8.99 N/mm^2	Calculated, Sinnott *et al.,* 2009
9.	Design Temperature T = 150^0C	Sinnott *et al.,* 2009

4.2   Flow Chart of Programme for CSC
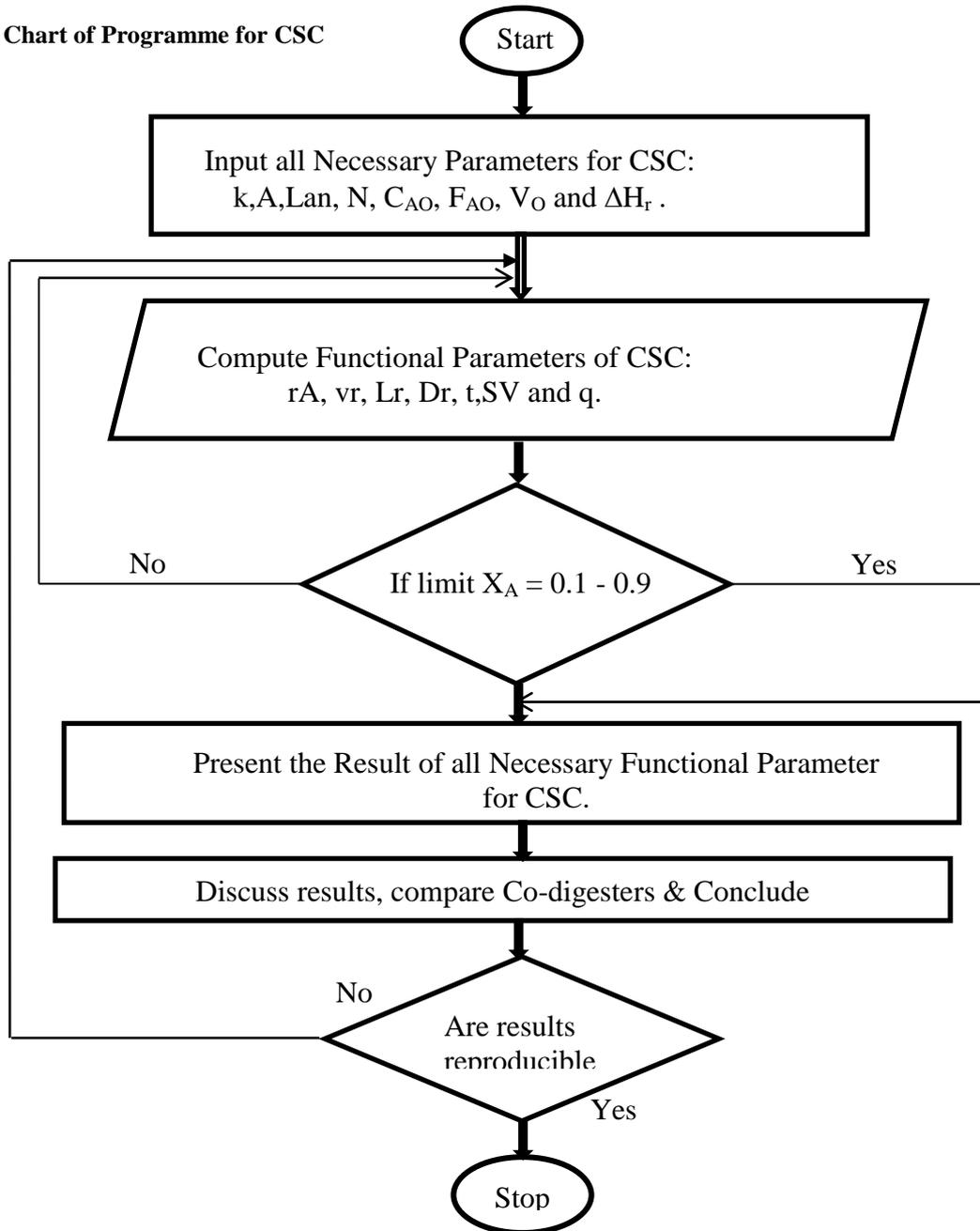
Fig. 3: Summarized Algorithm Outline Flow Chart Computational Model

5.0   RESULTS AND DISCUSSION

Table 2 shows the results of the Mathlab simulations to obtain functional parameters of CSTR with respect to X_A (fractional conversion).

X_A	$(-r)_A$	V_{CSTR}	D_{CSTR}	L_{CSTR}	τ_{CSTR}	Sv_{CSTR}	q_{CSTR}
0.1	0.153387	0.12387	0.428808	0.857616	0.263553	3.79431	3.834675
0.2	0.136344	0.278707	0.561898	1.123795	0.592993	1.68636	3.4086
0.3	0.119301	0.477783	0.672489	1.344977	1.01656	0.98371	2.982525
0.4	0.102258	0.743218	0.779196	1.558392	1.581315	0.632385	2.55645

Table 2 Functional parameters results of CSTR with fractional conversion

0.5	0.085215	1.114827	0.891957	1.783913	2.371973	0.42159	2.130375
0.6	0.068172	1.672241	1.021036	2.042071	3.557959	0.28106	1.7043
0.7	0.051129	2.601263	1.183049	2.366098	5.534603	0.180681	1.278225
0.8	0.034086	4.459309	1.415893	2.831786	9.487891	0.105398	0.85215
0.9	0.017043	10.03344	1.855345	3.71069	21.34775	0.046843	0.426075

5.1 Effect of Fractional Conversion
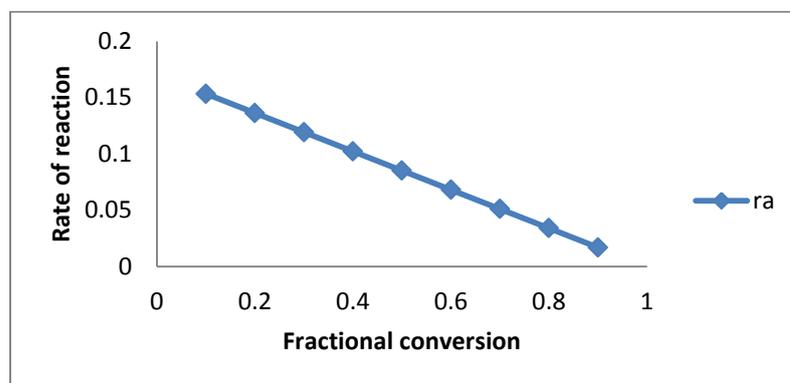
Figure 4: Rate of reaction against fractional conversion

Figure 4 shows the rate of reaction with fractional conversion. The rate of reaction is inversely proportional to the fractional conversion. This means that at higher fractional conversion, the rate of reaction is very small and high volume of methane gas.

5.3 Effect of Fractional Conversion on Volume of Reactors
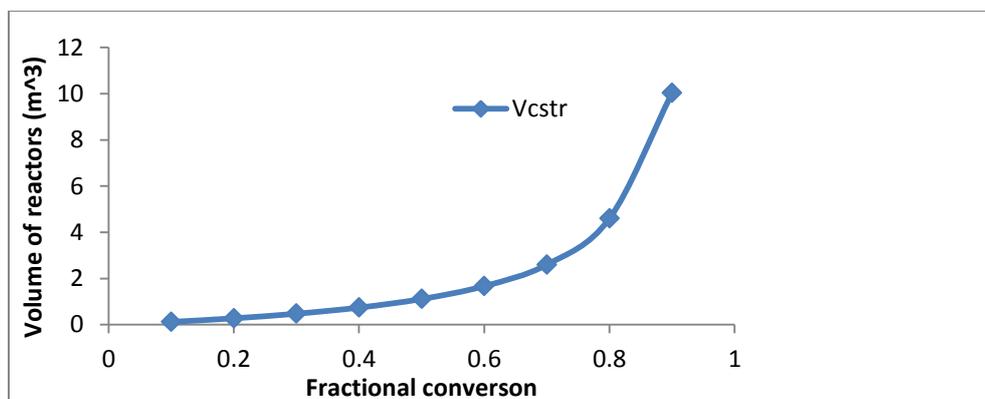
Figure 5: Volume of reactors (CSTR) versus Fractional conversion

Figure 5 depicts the volume of reactors continuous stirred tank reactor varying with fractional conversion. Comparatively, the volume of CSTR is high at X_A=0.9. Generally, the volume of the reactors increases exponentially as fractional conversion increases.

5.4 Effect of Fractional Conversion on Diameter of Reactors
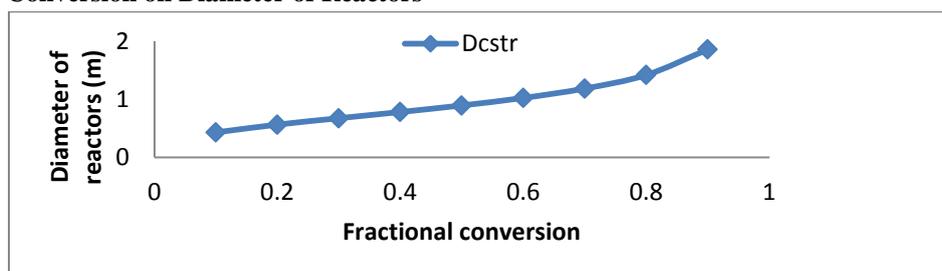
Figure 6: Diameter of reactors against Fractional conversion

Figure 6 shows the diameter of the reactor varying with fractional conversion. The diameter of the reactors (CSTR) generally increases as fractional conversion.

5.5   Effect of Fractional Conversion on Length of Reactors
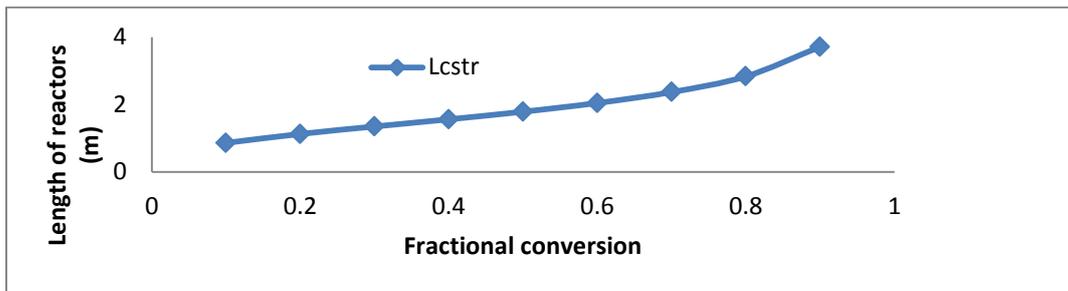
Figure 7: Length of reactors against Fractional conversion

Figure 7 depicts the length of the reactors varying with fractional conversion. The length increases as fractional conversion reaches maximum value of L_{CSTR}=3.71m

5.6   Effect of Fractional Conversion on Space Time of Reactors
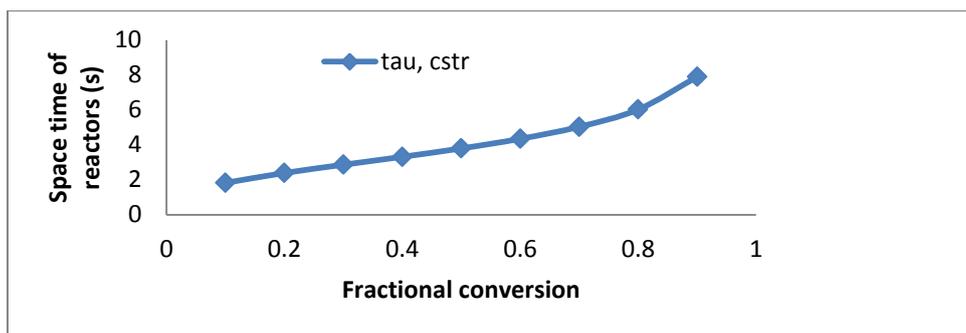
Figure 8: Space time of reactors against Fractional conversion

Figure 8 shows the variation of space time of reactors with fractional conversion. From the graph, the space time increases as fractional conversion increases . For instance, at X_A=0.9, τ_{PFR}=5.46secs.

5.7 Effect of Fractional Conversion on Space Velocity of Reactors
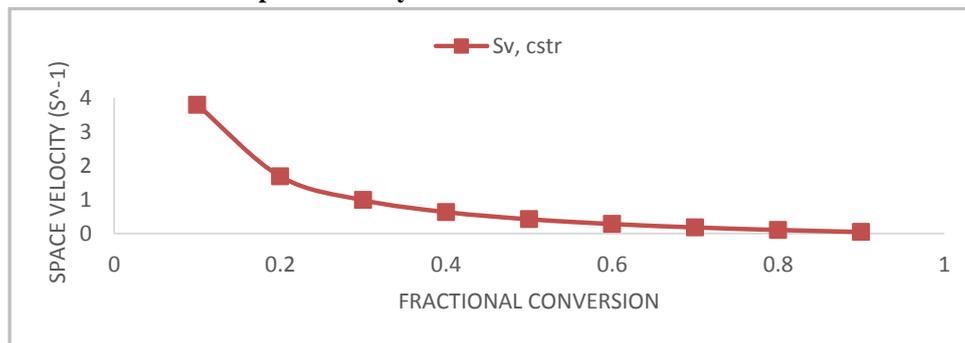
Figure 9: Space velocity of reactors against Fractional conversion

Figure 9 depicts the variation of space velocity of continuous stirred co-digester with fractional conversion. At same condition, the space velocity of reactors varies inversely to fractional conversion. At X_A= 0.9, S_{VCSTR} = 0.055^{-1}

5.8   Effect of Fractional Conversion on Heat Generated of Reactors
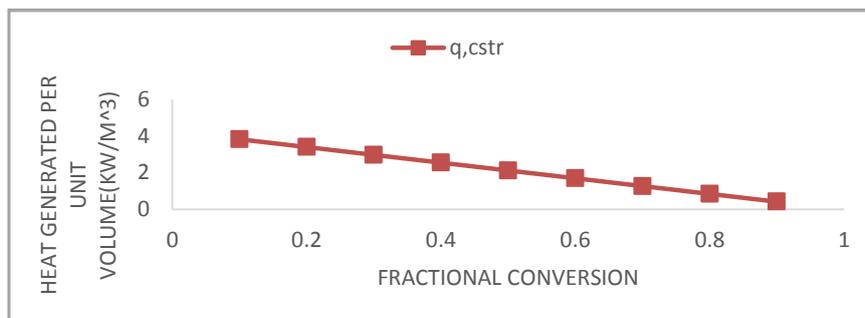
FIGURE 10: Heat generated per unit volume against Fractional conversion

FIGURE 10 shows the variation of heat generated per unit volume of reactors versus fractional conversion. Increase in fractional conversion results to decrease in heat generated per unit volume. q_{CSTR} is far less than q_{PFR} due to high volume produced from CSTR than PFR. At X_A=0.9, q_{CSTR}=0.426kw/m^3 and q_{PFR}=1.67kw/m^3. Very small heat is generated per unit for CSTR.

6.0   CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Hypothetical design equations for the modeling of Isothermal Continuous Stirred Co-digester unit is developed using cow-dung and grass clippings as source of raw materials. The developed models were capable of computing digester volume, length, space time space velocity, heat generation per unit volume and other associated engineering dimensions as a function of fractional conversion and parametric product design basics.

The results obtained were quit comparable and in-line with design expectations as volume, length and space time increases with increase in fractional conversion. While space velocity and heat generation per unit volume increase with decrease in fractional conversion.

6.2   Recommendations

This project was limited to the development of hypothetical design models for Continuous Stirred flow cow-dung and grass clippings Co-digester unit for biogas production at Isothermal condition using Gompertz kinetic model. Therefore, authors I recommend that further work should be carried out on the following;

- Cow-dung and grass clippings co-digester units should be developed for the simulation of the functional design dimensions using Gompertz kinetic model at non-isothermal condition of continuous and plug flow co-digester units at steady state.
- Isothermal condition of plug flow co-digester for cow-dung and grass clippings
- Cow-dung and grass clippings co-digester heat exchanger units should be developed for the simulation of the functional design dimensions using Gompertz kinetic model at both Isothermal and Non-isothermal condition.
- Evaluate the performance criteria for all co-digester types in other to ascertain the optimal product routes.

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MENCLATURE

Symbol	Definition	Unit
M_A	Molecular Weight of Glucose	Kg/mol
M_B	Molecular Weight of Carbondioxide	Kg/mol
M_C	Molecular Weight of Methane	Kg/mol
G_A	Mass Flow Rate of Glucose	Kg/s
G_B	Mass Flow Rate of Carbondioxide	Kg/s
G_C	Mass Flow Rate of Methane	Kg/s
$\overline{V}_A$	Specific Density of Glucose	m^3/kg
$\overline{V}_B$	Specific Density of Carbondioxide	m^3/kg
$\overline{V}_C$	Specific Density of Methane	m^3/kg
Q_A	Volumetric Flow Rate of Glucose	m^3/s
Q_B	Volumetric Flow Rate of Carbondioxide	m^3/s
Q_C	Volumetric Flow Rate of Methane	m^3/s
V_O	Total Volumetric Flow Rate of Reactants	m^3/s
C_{AO}	Initial Concentration of Reactant	mol/m^3
P_O	Initial Pressure	N/m^2
T_O	Initial Temperature of Feed	^oK
R	Gas Constant	$Nmmol^{-1}k^{-1}$
F_{AO}	Initial Flow Rate of Glucose	mol/s
Y	Cumulative of Specific Biogas Production	mL

A	Biogas Production Potential	mL
μ	Maximum Biogas Production Rate	day
λ	Lag Phase Period	day
T	Cumulative Time for Biogas Production	day
E	Mathematical Constant	-
P_i	Design Pressure	N/mm^2
D_i	Design Diameter	mm
J	Weld Type (Fully Radiographed)	-
f	Design Stress	N/mm^2
C_P	Full Face Gasket	-
T_O	Operating Temperature	^{O}C
X_A	Fractional Conversion	-
L_{st}	Stirrer Length	m
L_R	Reactor length	m
C	Allowance	m
V_{PFR}	Volume of Plug Flow Reactor	m^3
V_{CSTR}	Volume of Continuous Stirred Tank Reactor	m^3
t	Space Time	S
S_v	Space Velocity	S^{-1}
Q	Quantity of Heat	j/s
Q	Quantity of Heat Per Unit Volume of Reactor	Kw/m^3
Δ_P	Pressure Drop	Kpa
Y(t)	Rate Constant	ml