

Biokinetic Modeling and Simulation of Biomethane Synthesis from Organic Wastes in Anaerobic Reactor Regime

Ozurumba, Emeka Enyi¹; Titus Ndiele Amadi²

^{1,2}Department of Chemical & Petrochemical Engineering, River State University, Port Harcourt, Nigeria

Correspondent Author: titus.amadi@ust.edu.ng

Abstract— This work focuses on Biokinetic Modeling and Simulation of Biomethane Synthesis from Organic Wastes in Anaerobic Reactor Regime. A 30-chain reaction structure for Hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis (HAAM) biokinetics are adequately developed on the basis of analytically identified chemical composites of cow dung for biomethane synthesis. Principles of biokinetics and composites disintegration are employed interactively in modelling the biomethane synthesis performance over digestion time, and the simulation of the developed biokinetic models were carried out using MATLAB approach. Results depict that proportional increase in concentration of CO₂ and biomethane produced promotes decrease in cow dung concentration from 398.3746 g/L to 11.09 g/L within the first 230.5 hrs (10 days) of the digestion. The drop in feed concentration brought about 132.4509 g/L biomethane, 174.3920 g/L CO₂, and 193.3430 g/L enzyme – substrates (PEs) co-generated compounds. The products formation was identified to attain plateau after 230.5 hrs digestion of the cow dung feed. Within 500hr (21days), 90% fractional conversion of the feed was recorded, with approximately 60% average optimal yield of the biomethane and CO₂. The predictions of developed model shows that the model can be used to determine the effective time for optimal yield of biomethane in a bioreactor provided the volume of the biomass is known.

Keywords— Biokinetics, Modelling, Biomethane Synthesis, Organic Wastes, Anaerobic Reactor.

I. INTRODUCTION

Wastes (solid, liquid or gaseous) which are identified by most persons as toxic materials that promote negative health effects, unwanted, worthless and defective materials discarded after primary use by man. In most cases, wastes are regarded as materials with relatively minor economical values. Though some researchers are in the opinion that such ideology is not true in real life sciences by proving to many the relevance of waste when efficiently managed or recycled (Ugi *et al.*, 2023).

Greenhouse gases (GHGs) cause atmospheric environmental pollution. They emanate from organic wastes which are acted upon by microorganisms of which CO₂ and methane gas are highly potent (Lambert *et al.*, 2026; Nathaniel *et al.*, 2026). Presently wastes management has become so complex that the available facilities cannot cope with the continues increase in man's daily demand and needs.

Recycling is of great support to the economy, it provides a wide scope of job opportunities for youths as well as provides access to developments of new industries, that effectively depend on waste materials as their feedstock for production of re-useful materials. There are different types of waste recycling

approaches and classes as seen in Figure 1, and each has great support to wealth generation. The primary recycling approach focuses on the reuse of waste materials for the same purpose which the initial material was structured for. It involves the selective picking and reuse of plastics, cans, and cartoons, as packaging materials for same purposes which they were designed. While the Secondary recycling approach; which deals with the reuse of wastes material for a purpose farther from its original functionality (Geissdoerfer *et al.*, 2017; Lienig *et al.*, 2017).

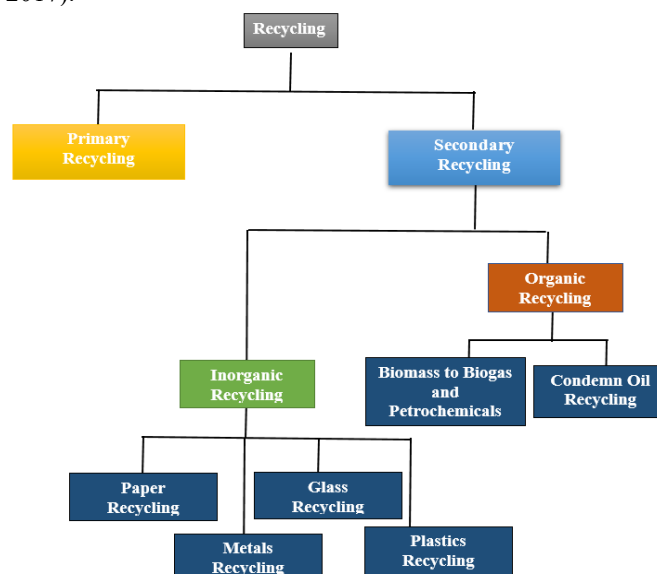


Figure 1: Classification of the Recycle (3Rs) waste management system

Among the above listed recycling methods or classes as seen in Figure 1, the biogas production method of wastes recycling is an essential waste to wealth measure that stands as a reliable method of energy source generation. Biogas generation from wastes recycling is presently the faith to energy grid for generation of low GHG emissivity fuel, that could help the world attain their global mission by 2050 (Awe *et al.*, 2018; Dai *et al.*, 2016; Deng *et al.* 2014; Igoni *et al.*, 2008; Marañón *et al.*, 2012). Biogas is a renewable gaseous form of energy source generatable from organic wastes - solid or liquid (Ahlamine *et al.*, 2024). Biogas is a product of anaerobic digestion in a bioreactor, generated from the bio-digestion of organic wastes in the absence of air, but in the presence of microbes which feed on the wastes and break down their giant hydrocarbons to

minute and less toxic composites such as methane (CH₄), 45 – 60% mass, carbon dioxide (CO₂) 25 – 40% mass, and with some limited amounts of hydrogen sulfide (H₂S), ammonia (NH₃), water vapor, and nitrogen (Abilmazhinov *et al.*, 2023). The %mass composites of biomass is a factor of the type, nature and concentration of the feed and enzymes, as well as the operating conditions and type of reactor used depending on the feedstock used in its production (Perry and Green, 2007; Mao, *et al.*, 2015). Biogas is an essential fuel that is identified to be of a low GHGs generation when compared to use of fossil fuels (natural gas, crude oil and coal).

The quest of attaining global mission 2050; aimed at discovering a low green house gas (GHGs) emission fuel source, as substitute to fossil fuel, and the associated problems with waste management has driven the interest of multiple researchers towards resolving two world class problems (wastes and energy) (Yong *et al.*, 2015).

Many more Researchers were able to assess the biogas production efficiency and yield from an anaerobic system (Mohamed *et al.*, 2023; Rabah, *et al.*, 2010; Zhang *et al.*, 2021; Bakraouia *et al.*, 2020). Some researchers have developed mathematical models that assessed the microbial behaviors on the biogas formation or yield system (Abilmazhinov *et al.*, 2023; Ahlamine *et al.*, 2024). Multiple biokinetic models have been introduced and applied for assessment of biogas productivity experimentally and simulatively (Pham *et al.*, 2018).

Despite all the studies carried out by different researchers, none was able to carry out biochemical process simulation as a validation of their used models using process computer software, as well as their inability to validate the residence time of the biodigester. It is the purpose of this paper to bridge these knowledge gaps via the development of biokinetic models that may be used to predict feed concentration gradient, optimal yield, and actual residence time of the biodigester. In the context of this study, cow dung is used as the feed for methane formation in a biodigester, taking into consideration the four stages for biogas (methane and carbon dioxide) production - hydrolysis, acidogenesis, acetogenesis and methanogenesis (HAAM).

II. MATERIALS AND METHODS

2.1 Materials

Fundamentally, the materials employed in the modeling and process simulation of biomethane production from organic wastes, using cow dung as feedstock are majorly:

- MATLAB Engineering software
- Handbooks in biochemical engineering
- Laptop

2.2 Methods

2.2.1 Kinetic Reaction Schematics Pathways Development for Biomass (Cow Dung) Anaerobic Digestion

In the simulation of the cow dung, 30 chemical reaction pathways are being considered as the kinetics of the cow dung digestion in the bioreactor based on the analytical results of cow dung composition (Karthik *et al.*, 2014). Hence considering the cow dung as the substrate with a known concentration (S) which is enzymatically decomposed into biogas, that is later treated to

achieve high purity biomethane, the fundamental reactions in the anaerobic biodigester are hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Karthik *et al.*, 2014).

These reaction processes collectively take place in the reactor at different reactor operating temperature, pressure and enzymatic efficiency. The biomethane is produced following the description in Figure 2, where all the biochemical reactions take place starting with the hydrolysis reaction phase.

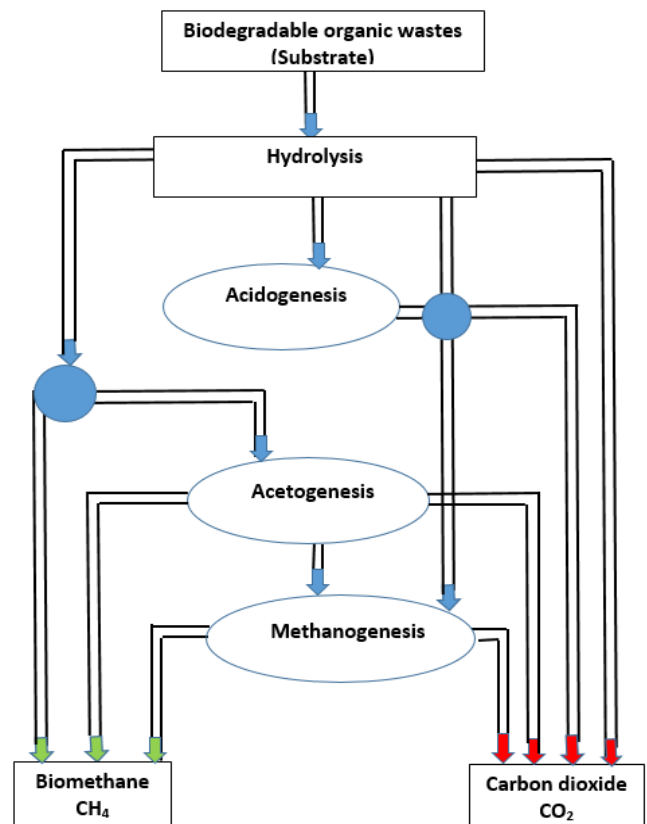
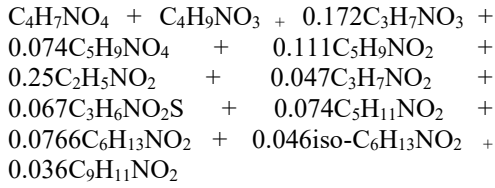
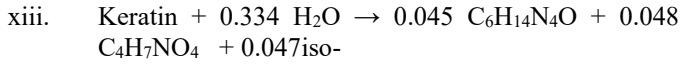


Figure 2: Schematic algorithm of biomass degradation in an anaerobic digester

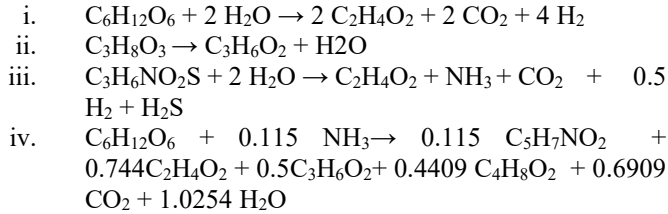
The 30 kinetic pathways for the digestion of cow dung as developed by (Karthik *et al.*, 2014) are shown below using the structural algorithm above (Figure 2).

a) Hydrolysis

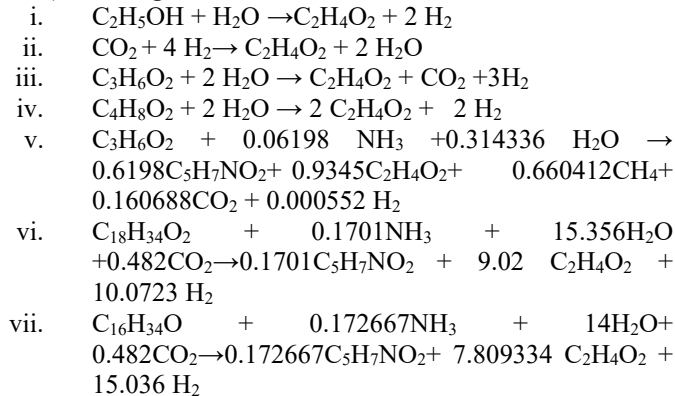
- $C_{12}H_{22}O_{11}$ (Sucrose) + H₂O (Water) → 2 C₆H₁₂O₆ (Dextrose)
- $C_6H_{10}O_5$ (Cellulose) + H₂O → C₆H₁₂O₆
- $C_5H_8O_4$ (Glutaric acid) + H₂O → 2C₂H₅O₂ + CO
- $C_5H_8O_4$ (Iso-Glutaric acid) + H₂O → C₅H₁₀O₅ (Xylose)
- $C_5H_{10}O_5$ (Xylose) → C₅H₄O₂ + 3H₂O
- $C_6H_{10}O_5$ + H₂O → 2 C₂H₆O + 2CO₂
- 2C₂H₆O (Ethanol) + CO₂ → 2 C₂H₄O₂ + CH₄
- $C_{57}H_{104}O_6$ (Triolein) + 3H₂O → C₃H₈O₃ + 3 C₁₈H₃₄O₂
- $C_{51}H_{98}O_6$ (Tripalmitin) + 8.4375H₂O → 4C₃H₈O₃ + 2.4375C₁₆H₃₄O
- $C_{37}H_{68}O_5$ (1-Palmitoyl-2-linoleoyl-sn-glycerol) + 4.2875 H₂O → 2.2 C₃H₈O₃ + 0.8875 C₁₆H₃₄O
- $C_6H_{10}O_5$ (3-Deoxyglucosone) + H₂O → 3CO₂ + 3 CH₄
- Protein + 6 H₂O → 6.5 CO₂ + 6.5 CH₄ + 3 NH₃ + H₂S



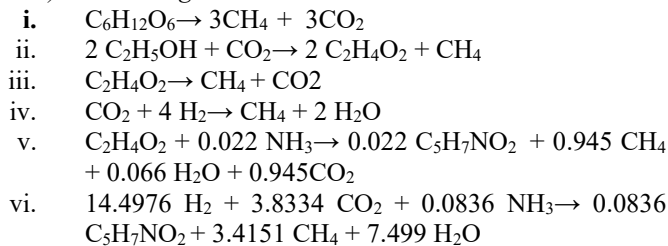
b) Acidogenesis



c) Acetogenesis



d) Methanogenesis



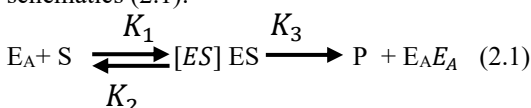
2.2.2 Development of Biokinetic Models for Anaerobic Digestion System

2.2.2.1 Process Modeling Assumptions for Anaerobic Digester

The following assumptions are being considered for effective modeling of the biomethane production system from bio-digestion process: i. Considering the system to be anaerobic; ii. Substrate – enzymes influence is regarded; iii. The reactor operates as a batch reactor; iv. The bioreactor operates adiabatic in nature (no heat loss or gain in the system); v. The system is isothermal and isobaric.

2.2.2.2 Determination of Anaerobic digestion Rate of Reaction

Considering the nature of the biokinetic reaction schematics to be consecutive reactions for cow dung digestion to biogas, via cow dung substrate (S) reaction with enzymes (E_A) in the digester to yield enzyme-substrate compounds (ES) which will furtherly digest into product gas (P), following the reaction schematics (2.1):



Now considering the methane generative kinetics of the system, at hydrolysis state of an anaerobic digester, as a function of the first principle of chemical material balance for a batch system, and under the influence of enzymes (E_A) as (Perry & Green, 2007; Nopharatana et al., 2007):

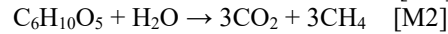
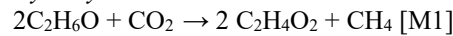
$$\left\{ \begin{array}{l} \text{Rate of reaction} \\ \text{of bioreactor} \\ \text{composites} \\ \text{in the unit volume} \end{array} \right\} = \left\{ \begin{array}{l} \text{Rate of Accumulation} \\ \text{in the bioreactor} \\ \text{unit volume} \end{array} \right\} \quad (2.2a)$$

Written as a function of microbial growth rate (μ) and the microbial cell density (X), gives:

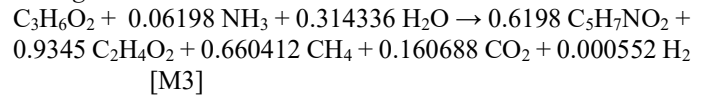
$$(-r_A) = \frac{dC_A}{dt} = \mu X = \frac{YdS}{dt} \quad (2.2b)$$

Fetching out of the developed biochemical kinetics of cow dung digestion, the biomethane generative reactions of the digester are mainly the M1 – M8 reaction chains seen below, the biomethane production modeling is subject to these reactions:

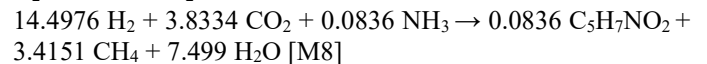
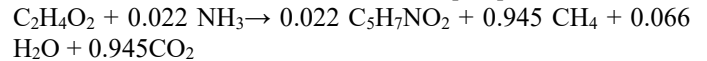
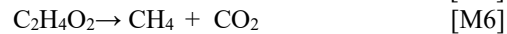
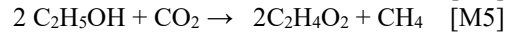
Hydrolysis



Acetogenesis



Methanogenesis



So, the rate law of the reactions with consideration of the equilibrium operations of the system as defined by Michaelis-Menton, is developed as (Wordu et al., 2026):

$$-\frac{dC_A}{dt} = -K_1 C_S^x C_B^y C_E + K_2 C_{ES} = K_3 C_{ES} \quad (2.3)$$

At equilibrium:

$$K_1 C_S^x C_B^y C_E = K_2 C_{ES} \quad (2.4)$$

Where;

$$C_E = C_{E0} - C_{ES} \quad (2.5)$$

Therefore, the enzymes – substrate concentration C_{ES} which is the continual bioreaction chain of the biomass degradation to CO₂ and biomethane as seen at the defined reaction schematics of the studied system above, is modeled as (Miebi et al., 2023):

$$C_{EAS} = \frac{K_1 C_S^x C_B^y C_{E0}}{K_2 + K_1 C_S^x C_B^y} \quad (2.6)$$

$$= \frac{C_S^x C_B^y C_{E0}}{K_{eq} + C_S^x C_B^y} = K_3 C_{ES} \quad (2.7)$$

$$\therefore \mu = r_{max} \frac{C_S^x C_B^y}{K_{eq} + C_S^x C_B^y} \quad (2.8)$$

Linearizing equation (3.17) to suit experimental derivatives:

$$\frac{1}{\mu} = \frac{K_{eq} + C_S^x C_B^y}{r_{max} C_S^x C_B^y} \quad (2.9)$$

Therefore:

$$\frac{1}{\mu} = \frac{K_{eq}}{r_{max}} \left(\frac{1}{C_S^x C_B^y} \right) + \frac{1}{r_{max}} \quad (2.10)$$

Which takes the form;

$$y = mx + C \quad (2.11)$$

Where:

K_{eq} = Substrate dissociation constant (hr^{-1})

Now, substituting equation (2.8) into equation (2.2) which is the rate of biomass dissociation into biomethane, expressed as:

$$(-r_A) = \left[\frac{r_{max} C_S^x C_B^y}{K_{eq} + C_S^x C_B^y} \right] X = \left[\frac{r_{max} S^x C_B^y}{K_{eq} + S^x C_B^y} \right] X \quad (2.12)$$

Also, the substrate concentration is expressed as:

$$S = C_{S0} \cdot e^{-k_1 t} \quad (2.13)$$

Where;

X = microbial cells density

$r_{max} = \mu_{max}$ = Specific growth rate (hr^{-1})

$S = C_S$ = Substrate concentration (g/L)

$S_0 = C_{S0}$ = Substrate initial concentration (g/L)

2.2.2.3 Residence Time and Biomethane Volume Modeling

Considering the residence time derived from the first principle

$$t_R = - \int_{S_0}^S \frac{1}{(r_A)} dS \quad (2.14)$$

$$= \frac{1}{X} \int_{S_0}^S \frac{K_{eq} + S^x C_B^y}{r_{max} S^x C_B^y} dS \quad (2.15)$$

$$= \frac{1}{X r_{max} C_B^y} \int_{S_0}^S \frac{K_{eq} + S^x C_B^y}{S^x} dS \quad (2.16)$$

Let:

$$u = K_{eq} + S^x C_B^y; \quad \therefore \frac{du}{dS} = x S^{x-1} C_B^y \quad (2.17a)$$

$$v = S^x; \quad \therefore \frac{dv}{dS} = x S^{x-1} \quad (2.17b)$$

Applying quotient rule:

$$\frac{dR}{dS} = \left\{ v \frac{du}{dS} - u \frac{dv}{dS} \right\} \frac{1}{v^2} \quad (2.18)$$

$$= \frac{S^x x S^{x-1} C_B^y - x S^{x-1} K_{eq} - x S^{x-1} S^x C_B^y}{S^{2x}} \quad (2.19)$$

$$= \frac{-x S^{x-1} K_{eq}}{S^{2x}} \quad (2.20)$$

Therefore:

$$dS = - \frac{S^{2x}}{x S^{x-1} K_{eq}} dR \quad (2.21)$$

$$\therefore t_{Bio} = - \frac{1}{X r_{max} C_B^y} \left(\frac{S^{2x}}{x S^{x-1} K_{eq}} \right) \int_{S_0}^S R dR \quad (2.22)$$

Now using the data above, the developed methanogenesis kinetic models are being accessed dynamically using MATLAB Simulink, and the results obtained from the simulation as seen in Table 1.

III. DISCUSSION

1. Feed – Products Concentration of Biomethane Product from Cow Dung

Figure 3 presents the relationship between cow dung methanogenesis composites concentration, in relation to the concentration of carbon dioxide and biomethane formed in the system over a period of 1000 hrs (42 days) actual time, which is the time considered by other reservoirs as the experimental time for cow dung digestion.

TABLE 1: Kinetic model simulation results for cow dung digestion system

ART (hr)	MRT (hr)	CDC (g/L)	SEC (g/L)	CH4 Conc. (g/L)	CO2 Conc. (g/L)	CH4 Yield (%)
0	0.00	398.38	0.00	0.00	0.00	0
100	28.48	59.61	234.1	51.25	138.50	0.13
200	63.09	11.39	193.3	132.45	174.39	0.33
300	108.35	0.09	106.4	218.05	193.49	0.55
400	174.04	0.01	61.01	237.33	196.04	0.60
500	369.23	0.01	50.66	237.21	196.04	0.60
600	369.23	9.34 e-4	49.21	237.21	196.04	0.60
700	369.23	3.07 e-4	49.21	237.21	196.04	0.60
800	369.23	1.57 e-4	49.21	237.21	196.04	0.60
900	369.23	1.57 e-5	49.21	237.21	196.04	0.60
1000	369.23	5.01 e-5	49.21	237.21	196.04	0.60

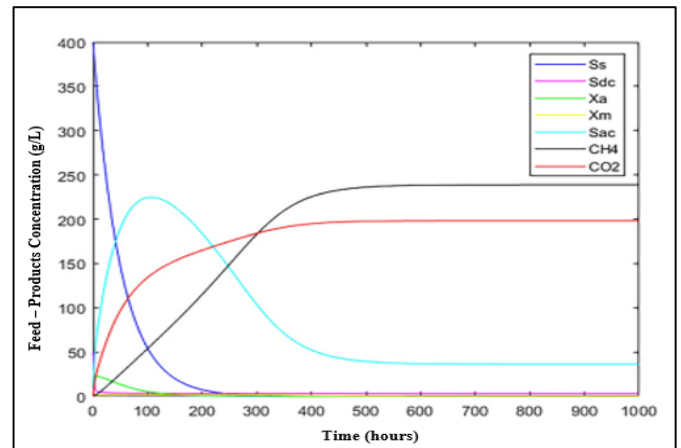


Figure 3: Concentration gradients of Feed – Product composites of cowdung digeston

The results depict a proportional increase in the concentration of the carbon dioxide and biomethane formed in the biogester with decrease in the cow dung concentration from 398.3746 g/L to 11.39 g/L. The concentration of the methanogenesis compounds depletes fast within the first 230.5 hrs of the digestion to 11.3922 g/L, in which 132.4509 g/L biomethane (33.25% methane yield), 174.3920 g/L carbon dioxide are formed, with 193.3430 g/L enzyme – substrates (PEs) compounds (Sac, Sdc, etc.). Thereafter, the cow dung digestion system attains plateau leaving the PE-compounds still generating (though in minute amounts) more CH_4 and CO_2 , which kept the concentration of the biomethane production system progressing till 500hrs of digestion was attained, yielding overall methane concentration of 237.3340 g/L and 196.0345 g/L for CO_2 . The PE compounds attain plateau at 61.0046 g/L concentration within 500hrs of cow dung digestion in the bioreactor. The result also shows a maximum biomethane yield of approximately 60%, which is attained within the 400hr to 500hr simulative (actual) time of cow dung digestion in the

bioreactor. This is in agreement with the aspen plus simulation result of the cow dung digestion system.

Enzymes – Substrate Compounds Concentration of Cow Dung in a Biodigester

The Enzymes – Substrate (PE) concentration, which is regarded in this work as the intermediate products generated from the Hydrolysis, Acetogenesis and Methanogenesis processes, involved in the cow dung digestion system, which are known to be promotive of the quality and quantity (yield) of biomethane formed, plays implicit paths in the performance of the digestion system. As depicted in Figure 4, the PEs concentrations change with increase in the active digestion time.

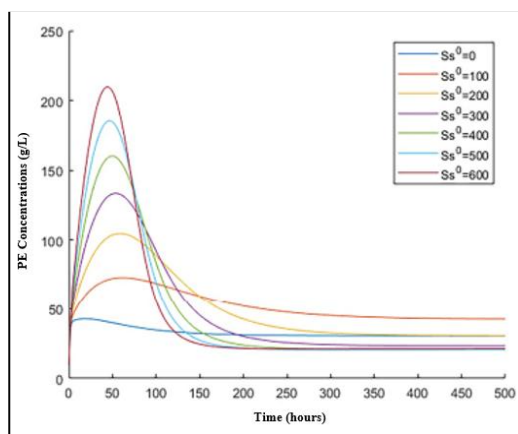


Figure 4: Relationship of the Enzyme-Substrate concentration with digestion time

The PEs compounds are first formed to attain a concentration range of 51.25 g/L for CH₄ and 138.50 g/L for CO₂ within the first 100 hrs of the cow dung digestion process. Thereafter, the cow dung starts depleting to increase the yield of the methane and CO₂ formed from 132.4509 g/L to 218.0536 g/L for CH₄ and 174.3920 g/L to 193.4905 g/L for CO₂ respectively between 200 and 300 hrs period of the cow dung digestion. This PEs depletion promotes the yield of the biomethane produced from 33% to 55% as shown in Table 1.

2. Comparative analysis between Actual and Residence time on C Dung digestion

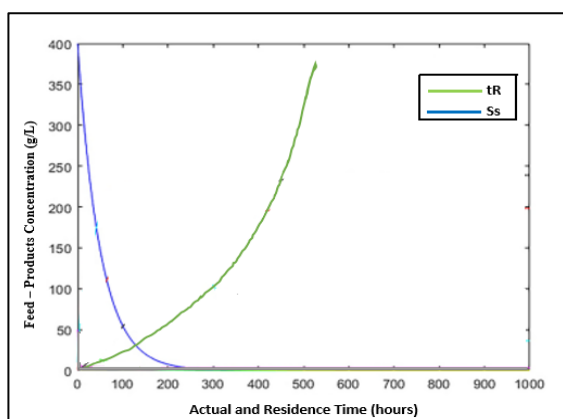


Figure 5: Developed model residence time and actual digestion Time

Figure 5 shows the relationship of the actual residence time with the developed model residence time. Increase in time proportionally, depletes the concentration of the cow dung in the biodigester. The simulation of the developed model shows that for a cow dung digestion system with a feed concentration of 398.3746 g/L, the residence time for optimal digestion is about 500 hrs (21 days) as seen in Table 1 (approx 60% yield). This shows that the remaining hours of the feed in the digester are not necessary for methane formation.

IV. CONCLUSION

The biokinetic model and simulation of biomethane taking into consideration the hydrolysis, acidogenesis, acetogenesis and methanogenesis (HAAM) reaction schematics were adequately developed on the bases of the analytically identified chemical composites of cow dung. The model was carried out using MATLAB Simulation programming tool. Predictions of the model showed a proportional increase in the concentration of the carbon dioxide and biomethane formed in the biogester, with decrease in the cow dung concentration. Also, the model result shows a maximum biomethane yield of approximately 60%, which is attained within the 400hr to 500hr simulative (actual) time of the cow dung digestion in the bioreactor. The biokinetic model developed in this study, and its validation using process simulation tool which is in agreement with the actual data, can be used to determine the effective time for optimal yield of biomethane in a bioreactor provided the volume of the biomass is known.

ACKNOWLEDGEMENT

We want to sincerely appreciate all the Technologists and Laboratory Technicians in Chemical & Petrochemical Engineering Department, Rivers State University, Port Harcourt for their assistance during the experimental aspect of this work.

REFERENCES

- [1] Awe, O. W., Lu, J., Wu, S., Zhao, Y., Nzihou, A., Lyczko, N., & Minh, D.P. (2018). Effect of oil content on biogas production, process performance and stability of foodwaste anaerobic digestion, Waste Biomass Valorization. *American Journal of Social and Management Sciences*, 9(12), 2295 - 2306.
- [2] Ahlamine, I., Alla, A. & Khattabi, N.E (2024). Mathematical analysis of an anaerobic digestion model for biogas production from solid waste. *Scientific Research*, 14, 25934.
- [3] Bakraouia M., Karouacha F., Ouhammoua B, Lahboubib N., El Gnaouia Y., Aggoura M., El & Baria H (2020). Kinetics study of methane production from anaerobic digestion of sludge and wastewater recycled pulp and paper by different models' simulation. *International Journal of Smart Grid and Clean Energy*, 9(1), 1 – 10. doi: 10.12720/sgce.9.1.170-179.
- [4] Dai, X.; Li, X.; Zhang, D.; Chen, Y.; Dai, L., (2016). Simultaneous enhancement of methane production and methane content in biogas from waste activated sludge and perennial ryegrass anaerobic co-digestion: The effects of pH and C/N ratio. *Bioresour. Technol.*, 216: 323-330.
- [5] Deng, Y.; Xu, J.; Liu, Y.; Mancl, K., (2014). Biogas as a sustainable energy source in China: regional development strategy application and decision making. *Renewable Sustainable Energy Rev.*, 35, 294-303.
- [6] Geissdoerfer, Martin; Savaget, Paulo; Bocken, Nancy M.P.; Hultink, Erik Jan (2017). The Circular Economy – A new sustainability paradigm. *Journal of Cleaner Production*. 143: 757–768.
- [7] Igoni, A.H., Ayotamuno, M.J., Eze, C.L., Ogaji, S.O.T., & Probert, S.D., (2008). Designs of anaerobic digesters for producing biogas from municipal solid waste, *Applied Energy*, 85 (6), 430–438.

- [8] Karthik Rajendran, Harshavardhan R. Kankanala, Magnus Lundin, Mohammad J. Taherzadeh (2014). A novel process simulation model (PSM) for anaerobic digestion using Aspen Plus. *Bioresource Technology*, Vol 168, 7-13. <https://doi.org/10.1016/j.biortech.2014.01.051>.
- [9] Lambert M. N., Ugi F. B., Wordu A. A., Ehirim E. O., Gloria T. T., Ugi B.U., Nathaniel, O. O.7, James B. J., Oba I. (2026) Mathematical Modeling and Process Simulation of Packed Bed Reactor for Methanol Synthesis from Carbon Dioxide Hydrogenation, *International Journal of Engineering and Advanced Technology Studies*, 14 (1), 64-97.
- [10] Mao, Chunlan; Feng, Yongzhong; Wang, Xiaojiao; Ren, Guangxin (2015). "Review on research achievements of biogas from anaerobic digestion". *Renewable and Sustainable Energy Reviews*. 45: 540–555.
- [11] Miebi N. Lambert, Fredrick B. Ugi, Wordu, A. A., Ehirim, E. O, Gloria, T. T, Benedict U. Ugi, Otie O. Nathaniel, Braide J James, & Israel Oba (2026). Mathematical Modeling and Process Simulation of Packed Bed Reactor for Methanol Synthesis from Carbon Dioxide Hydrogenation. *International Journal of Engineering and Advanced Technology Studies*, 14 (1), 64-97.
- [12] Mohamed Ali A, Alam MZ, Mohamed Abdoul-latif F, Jami MS, Gamiye Bouh I, Adebayo Bello I, Ainane T. (2023) Production of Biogas from Food Waste Using the Anaerobic Digestion Process with Biofilm-Based Pretreatment. *Processes*; 11(3):655. <https://doi.org/10.3390/pr11030655>
- [13] Nathaniel, O. O., Wordu A. A., Ehirim E. O, Gloria T. T., Lambert, Miebi N. (2026) Mathematical Modeling of Fluidized Bed Reactor for CO₂ Capture in a Typical Cement Producing Plant Existing in Nigeria, *International Journal of Engineering and Advanced Technology Studies*, 14 (1), 41-63
- [14] Nopharatana, A.; Pullammanappallil, P.C., & Clarke, W.P., (2007). Kinetics and dynamic modelling of batch anaerobic digestion of municipal solid waste in a stirred reactor. *Waste Management Journal. (Oxford)*, 27(5): 595-603.
- [15] Pham Van, D., Hoang, M., Pham Phu, S., & Fujiwara, T. (2018). Kinetics of carbon dioxide, methane and hydrolysis in co-digestion of food and vegetable wastes. *Global Journal of Environmental Science and Management*, 4(4), 401-412. doi: 10.22034/gjesm.2018.04.002
- [16] Perry, R. H. & Green, D. W. (2007). *Perry's Chemical Engineering Handbook*, 8th ed., McGraw Hill, USA.
- [17] Rabah, A. B., Baki, A. S. , Hassan, L. G. , Musa, M. & Ibrahim, A. D. (2010). Production of Biogas Using Abattoir Waste At Different Retention Time. *Science World Journal*, 5(4), 237-266 www.scienceworldjournal.org ISSN 1597-6343
- [18] Ugi, F. B., Ehirim, E. O., Wordu, A. A. and Ugi, B. U. (2023). Modelling, design and kinetics of novel Fred-Ugi environmental wastes converter reactor plant for crude oil distillates, minerals and petrochemical synthesis, *International Journal Environmental Engineering*, 12(2), 159–191.
- [19] Wordu, A. A; Briggs, M. I. F; Ugi, Fredrick. B; Ikenyiri P (2023). Thermodynamics, Kinetics and Equilibrium Analysis of Sulphur dioxide Oxidation in a Catalytic Reactor. *Scientific Research Journal of Engineering and Computer Science*, 3(3), 42-48
- [20] Yong, Z., Dong, Y., Zhang, X., & Tan, T., (2015). Anaerobic co-digestion of food waste and straw for biogas production. *Renewable Energy*, 78, 527–530.
- [21] Zhang H, An D, Cao Y, Tian Y, & He J. (2021). Modeling the Methane Production Kinetics of Anaerobic Co-Digestion of Agricultural Wastes Using Sigmoidal Functions. *Energies*, 14(2):258. <https://doi.org/10.3390/en14020258>