



Kinetics of Anaerobic Digestion of Unripe Plantain Peels

Chinenyenwa Nkeiruka Nweke^{1*} and Joseph Tagbo Nwabanne¹

¹Department of Chemical Engineering, Nnamdi Azikiwe University, P.M.B. 5025, Awka, Nigeria.

Authors' contributions

This work was carried out in collaboration between both authors. Author CNN managed the literature searches, performed the statistical analysis and wrote the first draft of the manuscript. Author JTN designed the study and wrote the protocol of the manuscript. Authors CNN and JTN managed the analyses of the study. Both authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JERR/2020/v17i217183

Editor(s):

(1) Dr. Heba Abdallah Mohamed Abdallah, National Research Centre, Egypt.

Reviewers:

(1) Maryama Hammi, University of Mohammed V, Morocco.

(2) Arun Kanti Guha, Southeast University, Bangladesh.

(3) Irma Pérez Silva, Universidad Autónoma del Estado de Hidalgo, México.

Complete Peer review History: <http://www.sdiarticle4.com/review-history/61119>

Original Research Article

Received 10 July 2020
Accepted 16 September 2020
Published 30 September 2020

ABSTRACT

This study was carried out to investigate the biogas production obtained from anaerobic digestion of unripe plantain peels (PP) and the kinetics of the digestion process. 400 g of dried and shredded unripe plantain peels were mixed with 200 ml of water and put into 1 L digester and observed for biogas for hydraulic retention time (HRT) of 15 days by the method of downwards displacement. The cumulative biogas volume obtained after digestion was 285 ml. The COD removal efficiency of 72.5% was achieved. The kinetics of PP digestion was evaluated using first order, Monod, Contois and, Grau second-order models. Results showed that the kinetics of anaerobic digestion of PP followed the first-order model with a constant (K) of 0.095 day^{-1} . Monod kinetics was evaluated and the maximum rate of substrate utilization (K), the half velocity constant (K_s), endogenous decay coefficient (K_d), biomass growth yield (Y) and, maximum specific microorganism growth rate (μ_{max}) obtained were 0.7615 day^{-1} , 16.20 mg/l , 0.0047 day^{-1} , $0.0112 \text{ mgVSS mgCOD}^{-1}$ and, 0.009 day^{-1} respectively. These results revealed that inoculation would be required to increase the rate and volume of biogas production. Both first-order and Monod models gave a high coefficient of determination indicating that first order and Monod models can be used to model the digestion of PP. Contois model gave values of μ_{max} and β as 0.011 day^{-1} and $0.644 \text{ mgCOD mgVSS}^{-1}$ respectively. The result obtained has shown that the digestion of PP did not follow second-order kinetics.

*Corresponding author: Email: chidar12000@yahoo.com;

Keywords: Anaerobic digestion; unripe plantain peel; biogas; kinetics.

ABBREVIATIONS

APHA : American Public Health Association.
 COD : Chemical Oxygen Demand.
 HRT : Hydraulic Retention Time (day).
 K : First Order Inactivation Rate Coefficient (1/day).
 K : Maximum Rate of Substrate Utilization (day⁻¹).
 K_d : Endogenous Decay Coefficient (day⁻¹).
 K_s : Half-velocity constant, mg/l.
 S₀ : Initial value of COD before the onset of the experiment (mg/l).
 S_e : COD value after every five days on charging the digester (mg/l).
 t : Time for batch digestion, day.
 TSS : Total Suspended Solid.

$U = \frac{dS}{dt} X$ = Rate of Substrate Utilization (mg COD/L/day.)

X : Average Total Suspended Solid (biomass concentration) (mg/l).

Y : Biomass yield (mg/mg).

PP : Unripe Plantain Peel.

$\theta = \frac{x}{dx/dt}$: The mean cell residence time (day).

μ_{max} : Maximum Specific Growth Rate of Microorganisms (day⁻¹).

1. INTRODUCTION

Currently, the reliability of global energy supply lies mainly in fossil fuel sources such as natural gas, oil, and coal. However, their use as energy providers is under scrutiny because of the serious disadvantages encountered due to the limited supply of fossil fuel resources and the carbon dioxide emitted when these fossil fuels are burned [1;2]. Alternative sources of energy are urgently sought with much focus on renewable which is obtained from biological treatment [3]. The advantages of biogas are that it reduces emissions of pollutants because it does not contain carbon and will promote the creation of jobs as well as save the cost of importation of fossil fuels [4]. Nigeria is a country that is rich in renewable energy resources [5]. Nigeria is one of the largest producers of plantain. However, the wastes generated from its use when disposed of improperly lead to environmental degradation [6]. These wastes can be treated by biological means through anaerobic digestion which produces biogas. The hydrolysis, acidogenesis, acetogenesis and the methanogenesis are the four stages of anaerobic digestion and the performance of each stage depend on the microorganisms involved in these stages [7]. Other forms of obtaining biogas are with the use of the thermophilic biogas plant inoculated at a temperature of 55°C (Hansen method) or the mesophilic biogas plant (Moller method) [8]. The kinetic model is used to

evaluate the anaerobic digestion process and the behavior of microorganisms in the anaerobic digester. Kinetic models determine if anaerobic digestion could favor the generation of biogas as the end-product of the treatment process [9]. The purpose of the study was to investigate the production of biogas from the batch anaerobic digestion of unripe plantain peels (PP). Also, first-order, Monod, Contois, and Grau second-order models were used to study the kinetics of the digestion process.

2. MATERIALS AND METHODS

2.1 Experimental Procedure

A one-liter batch anaerobic digester was connected by downward displacement to a measuring cylinder held by a retort stand to measure the volume of biogas produced. 200 g of the substrate and 400 ml of distilled water were mixed thoroughly to obtain a working volume of 600 ml before the digester was closed tightly with the rubber cap and observed for biogas production. Some quantity of the waste/water was collected after every three days during the retention period from a pipe in the digester and analyzed for TSS with the standard method of [10], whereas COD and pH analyses were done using the standard methods of [11] respectively for the kinetic study. The kinetic evaluation was evaluated with a 2010 version of Microsoft excel.

2.2 Kinetics Study

The kinetics of microbial activity and substrate utilization was evaluated with the first order, Monod, Contois, and Grau second-order models with the use of the experimental data obtained.

2.2.1 First-order model

The utilization of the limited substrate consumption could be described by assessing the first-order reaction equation [9] as shown in equation (1):

$$\frac{-dS}{dt} = K_r S \quad (1)$$

Where S is the substrate concentration

t is the hydraulic retention time (HRT)

K_r is the first-order inactivation rate constant

The equation describes the microbial exponential growth. The concentration of the substrate can be written as the exponential biomass growth as the substrate is consumed where the substrate concentration of the influent is proportional to the substrate concentration of the effluent and the retention time used as seen in equation (2) [12]:

$$S_e = S_0 \exp(-K_r t) \quad (2)$$

where S_e is the substrate concentration of the effluent (mg/l), S_0 is the substrate concentration of the influent (mg/l),

t is the hydraulic retention time (day)

The application of natural logarithm is given to both sides of equation (2) to find out if the anaerobic digestion of PP followed the first-order reaction as shown in equation (3) [13;14]:

$$\ln\left(\frac{S_e}{S_0}\right) = -K_r t \quad (3)$$

where K_r is the slope known as the first-order inactivation rate coefficient (day⁻¹) obtained from a linear plot of $-\ln(S_e/S_0)$ against t .

2.2.2 Monod model

For the Monod kinetics, the rate of substrate utilization, r_{su} can be expressed as [15]:

$$r_{su} = \left(\frac{dS}{dt}\right)_u = \frac{1}{Y} \left(\frac{dX}{dt}\right)_g = \frac{1}{Y} \left(\frac{\mu_m S}{K_s + S}\right) X \quad (4)$$

Where $\left(\frac{\mu_m S}{K_s + S}\right)$ is called the Monod's expression and

$$r_{su} = -\frac{r_g}{Y} \quad (5)$$

Where

$$r_g = \left(\frac{dX}{dt}\right)_g = \mu X = \left(\frac{\mu_m S}{K_s + S}\right) X \quad (6)$$

and r_g is the volumetric cell production rate (g VSSm⁻³)

Equation (6) is known as the rate of bacterial growth or volumetric cell production rate (g VSSm⁻³ day⁻¹). Hence,

$$r_{su} = -\frac{r_g}{Y} = -\frac{1}{Y} \frac{\mu_m SX}{K_s + S} = -\frac{K SX}{K_s + S} \quad (7)$$

where

$$K = \frac{\mu_m}{Y} \quad (8)$$

and K is the maximum rate of substrate utilization (day⁻¹)

K_s is the half-velocity constant/ saturation constant (mg/l)

Y is the biomass yield/microbial growth yield (mgVSS mgCOD⁻¹)

X is the average total suspended solids (mg/l)

Where μ_{max} is the maximum specific growth rate of micro-organisms (day⁻¹)

μ_{max} indicates the maximum growth rate of microorganisms when the substrate is being used up at its maximum rate [16].

When $\left(\frac{dS}{dt}\right)_u$ has a positive value,

$$U = \frac{\left(\frac{dS}{dt}\right)_u}{X} = \frac{KS}{K_s + S} \quad (9)$$

where $U = \frac{dS/dt}{X}$ = Specific rate of substrate

utilization (mg COD/L/day)

Inverting gives

$$\frac{1}{U} = \frac{K_s + S}{KS} = \frac{K_s}{KS} + \frac{S}{KS} = \frac{K_s}{K} \frac{1}{S} + \frac{1}{K} \quad (10)$$

A linear plot of $\frac{1}{U}$ against $\frac{1}{S_e}$ gives the slope and intercept as K_s and K respectively.

The greater the value of K (the maximum rate of substrate utilization), the smaller the size of the reactor for design application [17]. K_s indicates the change in the specific growth rate of bacteria as the concentration of the growth-limiting substrate changes [17].

As obtained from [18],

$$r_g = YU - K_d X \quad (11)$$

And

$$U = \frac{S_0 - S}{\theta X} \quad (12)$$

Combining equation (11) and equation (12), $\frac{1}{\theta}$ becomes

$$\frac{1}{\theta} = YU - K_d \quad (13)$$

Where θ is the mean cell residence time (day)
 K_d is the endogenous decay coefficient (day^{-1})

θ for batch reactors was evaluated from [19;14] as,

$$\theta = \frac{X}{dX/dt} \quad (14)$$

The evaluation of Y and K_d was obtained from a linear plot of $\frac{1}{\theta}$ against. The value, K_d

indicates the net amount of sludge to be handled and the size and cost of the sludge handling equipment since the smaller value of Y and K_d confirms a higher production of sludge [20;17]. The total amount of sludge produced during anaerobic digestion is estimated from the value of Y [20].

2.2.3 Contois model

Contois and Monod's models are similar from the relationship between the specific growth rate and the rate-limiting substrate concentration [21;22] as

$$\mu = \frac{\mu_{max} S}{\beta X + S} \quad (15)$$

where

$$\mu = \frac{1}{\theta_c} + K_d \quad (16)$$

Substituting Equation (15) into (16)

$$\frac{\mu_{max} S}{\beta X + S} = \frac{1}{\theta_c} + K_d \quad (17)$$

Under steady-state conditions, the rate of change of substrate concentration (dS/dt) is negligible, and Equation (18) is obtained.

$$\frac{S_0 - S}{\theta_H} = \frac{X}{Y} \left(\frac{1}{\theta_c} + K_d \right) \quad (18)$$

Rearranging Equation (18), Equation (19) is obtained.

$$\frac{S_0 - S}{\theta_H X} = \frac{1}{Y \theta_c} + \frac{K_d}{Y} \quad (19)$$

The kinetic parameters, Y , and K_d are evaluated from the slope and intercept of the linear plot of Equation (13) or (19). Y and K_d values are the same for Monod and Contois equations. θ_c is the mean cell residence time (day).

The kinetic parameters, μ_{max} and β could be determined from the plot of Equation (20),

$$\frac{\theta_c}{1 + \theta_c K_d} = \frac{\beta}{\mu_{max}} \frac{X}{S} + \frac{1}{\mu_{max}} \quad (20)$$

Where μ_{max} = maximum specific growth rate of microorganisms (day^{-1})

β = Contois kinetic coefficient (mgCOD mgVSS^{-1})

X = Average total suspended solid (biomass concentration) (mg/l)

S = Effluent substrate concentration (mg/l)

2.2.4 Grau second-order model

The general equation of Grau second-order kinetic model [23;21] is shown in Equation (21),

$$-\frac{dS}{dt} = k_2 X \left(\frac{S_e}{S_0} \right)^2 \quad (21)$$

Where $-dS/dt$ = rate of substrate removal (mg/l/day)

k_2 = second-order substrate removal rate constant (day^{-1})

S_0 = Influent substrate concentration (mg/l)

S_e = Effluent substrate concentration (mg/l)

X = Average total suspended solid (biomass concentration) (mg/l)

Integrating and linearizing Equation (21) gives,

$$\frac{S_0 \times HRT}{S_0 - S_e} = HRT + \frac{S_0}{k_2 X} \quad (22)$$

$S_o - S_e/S_o$ indicates the substrate removal efficiency (E) and S_o/k_2X is a constant called 'a'. The equation for the plot becomes

$$\frac{HRT}{E} = a + bHRT \quad (23)$$

Where constants a (day^{-1}) and b (dimensionless) are evaluated in the plot of $\frac{HRT}{E}$ against HRT from the intercept and slope respectively. k_2 is evaluated by inserting the values of S_o and X into $\frac{S_o}{k_2X}$ [20].

The COD removal efficiency during anaerobic digestion was calculated thus:

$$\begin{aligned} \text{COD removal efficiency (\%)} \\ = \frac{\text{Initial COD} - \text{Final COD}}{\text{Initial COD}} \times 100\% \end{aligned} \quad (24)$$

3. RESULTS AND DISCUSSION

3.1 The Production of Biogas

The effect of hydraulic retention time on the biogas volume produced on a three-day interval basis and the cumulative biogas production are shown in Figs. 1 and 2. The optimum operating condition for the treatment of PP was 15 days HRT. [7] reported that mesophilic digestion could be accomplished within 15–30 HRT. The cumulative biogas volume of PP obtained at the end of the digestion process was 270 ml. Biogas

production started on the 3rd day and increased until the 6th day. The biogas volume produced began declining from the 6th day and was observed to stop by the 15th day. These observations explained the different phases or stages of biogas production which are the lag stage, the acidogenesis, acetogenesis, and methanogenesis stages [24].

3.2 Kinetic Modeling

3.2.1 First-order model

A plot for evaluating the order of reaction for PP digestion using $-\ln(S_e/S_o)$ versus t for first-order is shown in Fig. 3. The first-order kinetic data for PP digestion is shown in Table 2. Based on this study, the COD removal efficiency of 72.5% was achieved. A first-order inactivation rate constant (K_d) of 0.095 day^{-1} was obtained with a high coefficient of determination value of 0.9695 indicating that the kinetics of PP digestion followed the first-order reaction. A high regression coefficient confirmed that the kinetics of the digestion process was a first-order reaction [14]. The high regression coefficient obtained indicated that first-order kinetics could be used to describe the COD removal from PP digestion since the first-order model data was based on the change in the COD value obtained during digestion as explained in [25].

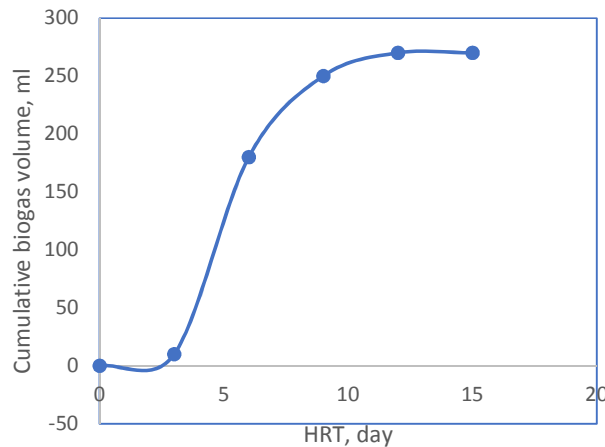


Fig. 1. Biogas volume with HRT after every 3-day interval for PP digestion

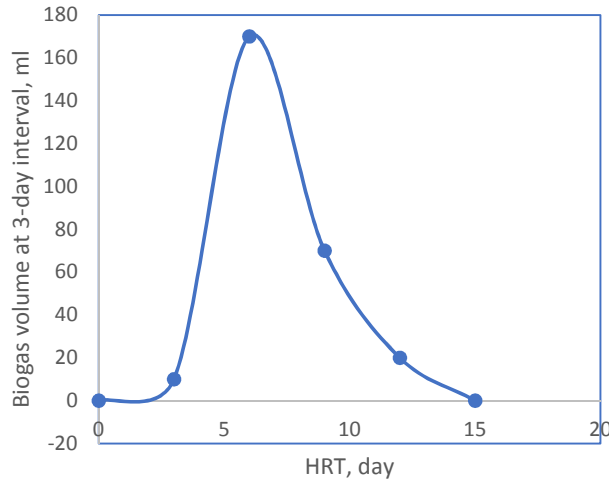


Fig. 2. Cumulative biogas volume with HRT on 3-day interval for PP digestion

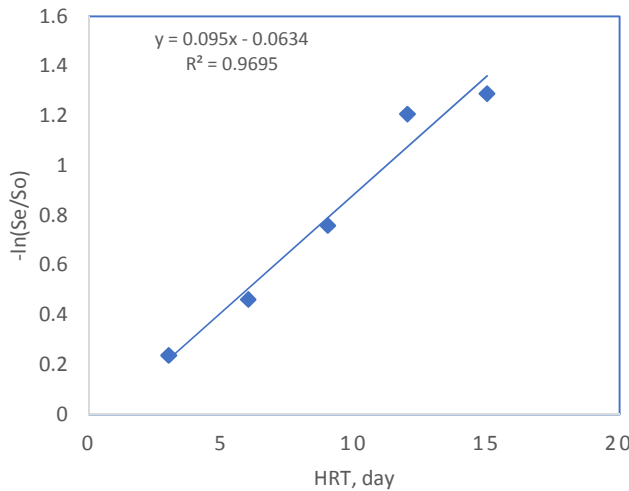


Fig. 3. Plot of first order kinetics for PP digestion

3.2.2 Monod model

From the plot of $\frac{1}{U}$ against $\frac{1}{S_e}$ in Monod kinetic model as shown in Fig. 4, the values of K and K_s determined were 0.7615 day^{-1} and 16.20 mg/l respectively. K represents the maximum rate of substrate utilization per unit mass of microorganisms. The constant K determines the volume of the reactor because an increase in the value of K leads to a smaller size of the reactor [26;17]. As a result, a greater volume of the biological reactor would be required for the treatment of PP. [26] reported that a rise in the content of inorganic substances would lead to a lower value of K when compared to degradable organic substances. The constant, K_s does not have a direct application for process design but only define the substrate concentration. It rather

explains the change in the specific growth rate of microorganisms [26]. [27] reported that wastewaters of low organic nature would have a lesser value of half velocity concentration. The half velocity concentration obtained in [27] from the anaerobic digestion of combined domestic and tannery wastewater was 122 mg/l and was higher than PP wastewater because of its high organic nature when compared to PP.

A graph of $1/\theta$ along the Y-axis against U along the X-axis for the evaluation of Y and K_d is expressed in Fig. 5. A best-fitted line was drawn to the origin of the plotted data from which Y and K_d were obtained from the slope and intercept as $0.0112 \text{ mgVSS mgCOD}^{-1}$ and 0.0047 day^{-1} respectively. How biomass is lost against substrate utilization is measured with the value of

Y. It estimates the volume of sludge resulting from the waste treatment. An increase in the size of sludge handling equipment would be obtained from a high amount of sludge production when the value of Y is high [20; 26]. The lower death rate obtained from PP digestion could have been due to the short HRT having a positive effect on microbial growth [27]. Wastewater of a lesser organic nature most times has a lower decay rate coefficient. The K_d value of 0.088 day^{-1} was obtained in [27] on combined domestic and tannery wastewater indicating that a higher volume of sludge will be produced from combined domestic and tannery wastewater when compared to PP.

The value of μ_{max} is based on the organism and the substrate utilized and occurs when the maximum substrate used equals the maximum rate of bacterial growth [20]. In this study, μ_{max} obtained for PP was very low (0.009 day^{-1}), indicating that the maximum specific growth rate of microorganism per day was low and explained that there was a high amount of biomass in the digester [28]. The R^2 values obtained from all the Monod kinetic plots for PP digestion were very high. The present study of PP digestion indicates that unripe plantain peels can be biologically

treated using anaerobic digestion. The Monod kinetic data for PP digestion is shown in Table 2.

3.2.3 Contois model

Fig. 6 was the Contois plot used for the determination of μ_{max} and β for PP digestion. Equation (20) was plotted and the kinetic parameters were evaluated from the intercept and slope of the plot respectively. The values of Y and K_d were $0.0112 \text{ mgVSS mgCOD}^{-1}$ and 0.0047 day^{-1} respectively. The values of μ_{max} and β were calculated as 0.011 day^{-1} and $0.644 \text{ mgCOD mgVSS}^{-1}$ respectively. The μ_{max} value obtained from both Contois and Monod models was comparable. A lower μ_{max} value reveals a decrease in the removal of the substrate due to varying reactor configurations [22]. The figure was curved and not linear since the kinetic data generated for the plot did not fit the Contois model. Hence, the kinetics of anaerobic digestion of unripe plantain peels (PP) could not be described with the Contois model. In conclusion, the Contois model cannot be applied for the kinetic analysis of PP digestion because it gave a low regression coefficient (R^2) value of 0.7738 [21].

Table 1. Result of Analyses for First order and Monod Kinetic Modelling from PP Digestion

HRT (day)	pH	Initial COD (S_o) (mg/l)	Effluent COD (S_e) (mg/l)	Initial TSS (X_o) (mg/l)	Effluent TSS (X_e) (mg/l)	Gas vol. (mL)	
						Interval	Cumulative
1	6.60	83.20		70.2		0	0
3	6.24		65.60		56.4	10	10
6	5.79		52.40		40.0	170	180
9	4.35		38.93		32.4	70	250
12	3.84		24.87		19.0	20	270
15	3.15		22.91		6.3	0	270

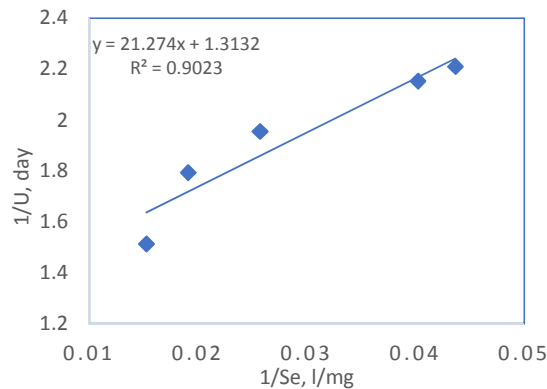


Fig. 4. Plot for evaluating K and K_s values for PP digestion

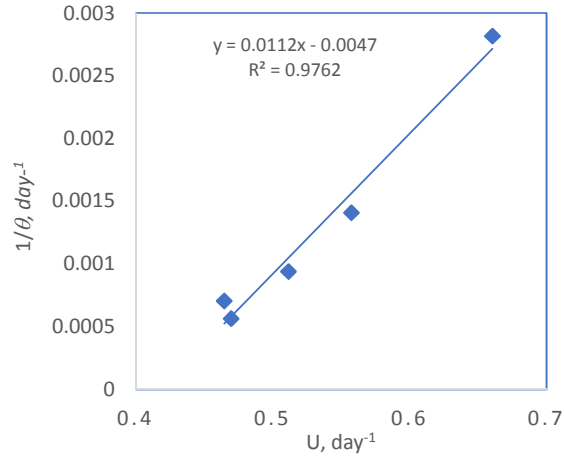


Fig. 5. Plot for the evaluation of Y and K_d for PP digestion

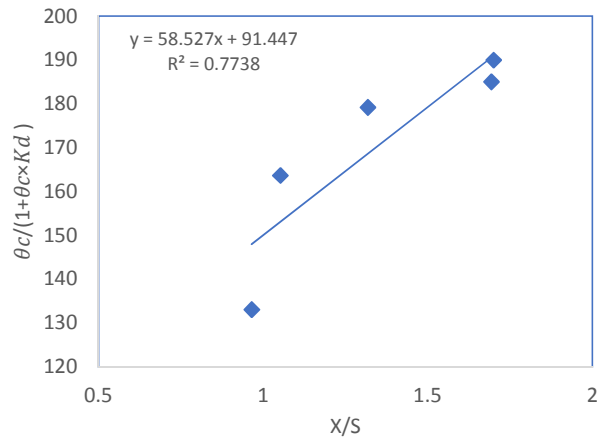


Fig. 6. Plot for determination of μ_{max} and β in Contois model for PP digestion

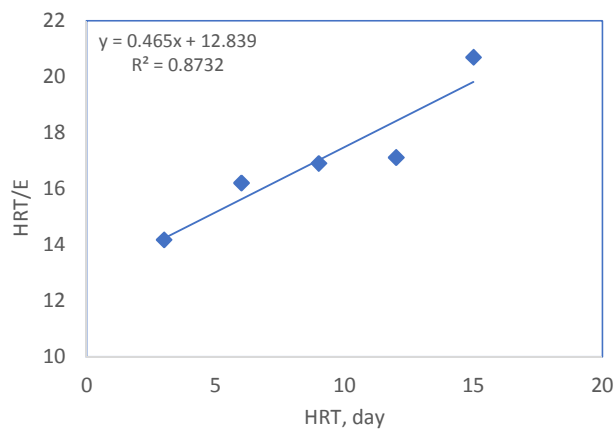


Fig. 7. Plot for determination of a , b and k for Grau second-order model for PP digestion

Table 2. Kinetic data for Grau second-order kinetic model for PP digestion

HRT (day)	Initial COD (S _o) (mg/l)	Effluent COD (S _e) (mg/l)	E% $\left(\frac{S_o - S_e}{S_o} \times 100\%\right)$	HRT/E $\left(\frac{HRT}{E} \times 100\%\right)$
1	83.20	-	-	-
3	83.20	65.60	21.15	14.18
6	83.20	52.40	37.02	16.21
9	83.20	38.93	53.21	16.91
12	83.20	24.87	70.11	17.12
15	83.20	22.91	72.46	20.70

Table 3. Kinetic parameters of Batch reactor treating PP waste

Kinetic models	Kinetic parameters	Values	Regression coefficient (R ²)
First-order	K _r (day ⁻¹)	0.095	0.9695
Monod	K (day ⁻¹)	0.7615	0.9023
	K _s (mg/l)	16.20	0.9023
	Y (mgVSS mgCOD ⁻¹)	0.0112	0.9762
	K _d (day ⁻¹)	0.0047	0.9762
	μ _{max} (day ⁻¹)	0.009	-
Contois	Y (mgVSS mgCOD ⁻¹)	0.0979	0.9371
	K _d (day ⁻¹)	0.0042	0.9371
	μ _{max} (day ⁻¹)	0.011	0.7738
	β (mgCOD mgVSS ⁻¹)	0.644	0.7738
Grau second-order	a (day ⁻¹)	12.839	0.8732
	b	0.465	0.8732

3.2.4 Grau second-order model

The kinetic data from PP digestion was generated for simulation into the Grau second-order model as shown in Table 2. The Grau second-order model plot is given in Fig. 7. The values of *a* and *b* were 12.839 day⁻¹ and 0.465 respectively. The correlation coefficient (R²) obtained was <0.9 and indicated that the anaerobic digestion of PP could not be described by the second-order model. Also, Fig. 7 was not linear but curved because the kinetic data used for the plot did not fit the Grau second-order model. Hence, the kinetics of anaerobic digestion of unripe plantain peels (PP) could not be described with the Grau second-order model. However, in [29], the correlation coefficient of 0.9955 was obtained from the kinetics study of the anaerobic digestion of ketchup industry wastewater using the Grau second-order model and reported that the kinetics of the process followed Grau second-order model, due to the high value of correlation coefficient obtained. The kinetic parameters calculated from the four models are given in Table 3.

4. CONCLUSION

The purpose of this study was to observe the efficiency of anaerobic digestion in the treatment of unripe plantain peels. The optimum operating condition for the treatment of PP was obtained as 15 days. Both first-order and Monod models effectively described the digestion of PP as observed from R² >0.9 values obtained from their plots. The first-order kinetic constant, K_r was 0.095 day⁻¹. The values of Monod kinetic coefficients *K*, *K_s*, *Y*, *K_d* and μ_{max} on COD removal basis were 0.7615 day⁻¹, 16.20 mg/l, 0.0112 mgVSS mgCOD⁻¹, 0.0047 day⁻¹ and 0.009 day⁻¹ respectively. The maximum rate of substrate utilization (*K*) known also as the COD removal rate constant can be considered when designing the digester to be used for the bio-treatment of unripe plantain peels. This was because the value of *K* obtained signified that a large volume of digester would be required. The present study will be a promising solution for the treatment of unripe plantain peels in areas, including Nigeria, where their disposal without

treatment causes environmental pollution. Pilot-scale studies can also be carried out to evaluate the treatment of unripe plantain peels using anaerobic digestion under field conditions to determine the necessary data for full-scale design.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Maloles JS, Pajares IG, Elegado FB. Comparative kinetics of the ethanol of *Zymomonas mobilis* with *Saccharomyces cerevisiae* using sugarcane and sweet sorghum syrup. *Journal of Engineering Technology and Education. The 2012 International Conference on Green Technology and Sustainable Development (GTSD 2012)*. Available: <https://pdfs.semanticscholar.org/2574/2ad38802fe1b032dc3cf9126ba67dee5d512.pdf> Accessed 2 March 2020.
2. Meintjes MM. Fermentation coupled with pervaporation: A kinetic study. Unpublished masters' thesis, school of chemical and minerals engineering, North-West University, Potchefstroom Campus. 2011. Available: <https://repository.nwu.ac.za/handle/10394/7283> Accessed 3 January 2020.
3. Puyate YT, Yelebe ZR. Estimation of monod kinetic parameters during aerobic digestion of biodegradable organic waste, part 2: Analysis based on microbial growth with effect of bioaugmentation. *International Journal of Engineering Research and Applications*. 2012;2(6):903-911.
4. Roopnarain A, Adeleke R. Current status, hurdles and future prospects of biogas digestion technology in Africa. *Renewable and Sustainable Energy Reviews*. 2017; 67:1162-1179.
5. Mshandete AM, Parawira W. Biogas technology research in selected sub-saharan African countries: A review. *African Journal of Biotechnology*. 2009; 8(2):116-125.
6. Longjan GG, Dehouche Z. Nutrient characterisation and bioenergy potential of common Nigerian food wastes. *Waste Management & Research*. 2018;36(5):426-435.
7. Meegoda JN, Li B, Patel K, Wang, LB. A review of the processes, parameters, and optimization of anaerobic digestion. *International Journal of Environmental Research and Public Health*. 2018; 15(224):1-16.
8. Pham, CH, Triolo, JM, Cu TTT, L. Pedersen, L, S. G. Sommer, SG. Validation and recommendation of methods to measure biogas production potential of animal manure. *Asian-Australasian Journal of Animal Sciences*. 2013;26(6):864-873. Available: <http://dx.doi.org/10.5713/ajas.2012.12623>.
9. Darwin MI, Fazil A. Performance and kinetic study of the anaerobic co-digestion of cocoa husk and digested cow manure with high organic loading rate. *INMATEH: Agricultural Engineering* 2018;55(2):131-140.
10. APHA. 2540 Solids: Total suspended solids dried at 103-105 °C, method 2540 D, Standard methods for the Examination of water and wastewater, American public health Association, Physical and aggregate properties. 2000;61. DOI: 10.2105/SMWW.2882.030
11. APHA. Standard Methods for the Examination of Water and Wastewater, 19th edition. APHA, AWWA, WEF/1995. APHA Publication; 1995.
12. Khan MT, Brule M, Maurer C, Argyropoulos D, Muller J, Oechsner H. Batch anaerobic digestion of banana waste-energy potential and modelling of methane production kinetics. *AgricEngInt: CIGR Journal of Open Access*. 2016;18(1): 110-128.
13. Emembolu LN, Nwabanne JT, Onu CE. Date removed Kinetic modeling of anaerobic digestion of restaurant waste water. *British Journal of Applied Science & Technology*. 2017;21(4):1-12.
14. Nwabanne JT, Okoye AC, Ezedinma HC. Kinetics of anaerobic digestion of palm oil mill effluent. *Canadian Journal of Pure & Applied Sciences*. 2012;6(1):1877-1881.
15. Chang R. Enzyme Kinetics (Chapter 10). In *Physical Chemistry for the Biosciences*, Sausalito (CA): University Science Books. 2005;363-371.
16. Bhunia P, Ghangrekar M. Analysis, evaluation, and optimization of kinetic

- parameters for performance appraisal and design of UASB reactors. *Bioresour. Technol.* 2008;99(7):2132-2140.
17. Haydar S, Aziz JA. Kinetic coefficients for the biological treatment of tannery wastewater using activated sludge process. *Pak. J. Engg. & Appl. Sci.* 2009; 5:39-43.
 18. Mardani S, Mirbagheri A, Amin MM, Ghasemian M. Determination of biokinetic coefficients for activated sludge processes on municipal wastewater. *Iran. J. Environ. Health. Sci. Eng.* 2011;8(1):25-34.
 19. Nweke CN, Nwabanne JT. Continuous process design model simulation for the anaerobic digestion of vegetable oil wastewater. *American Journal of Environmental Protection.* 2014;3(5):209-216.
 20. Nor Faekah I, Fatihah S, Mohamed ZS. Kinetic evaluation of a partially packed upflow anaerobic fixed film reactor treating low-strength synthetic rubber wastewater. *Helion.* 2020;6:1-7.
 21. Jijai S, Siripatana C, O-Thong S, Ismail N. Kinetic models for prediction of COD effluent from upflow anaerobic sludge blanket (UASB) reactor for cannery seafood wastewater treatment. *Jurnal Teknologi.* 2016;78(5-6):93-99.
 22. Isik M, Sponza DT. (2005) Substrate removal kinetics in an upflow anaerobic sludge blanket reactor decolorizing simulated textile wastewater. *Process Biochemistry.* 2005;40:1189-1198.
 23. Mekonnen A, Leta S, Njau KN. Kinetic analysis of anaerobic sequencing batch reactor for the treatment of tannery wastewater. *African Journal of Environmental Science and Technology.* 2017;11(6): 339-348.
 24. Patinvoh RJ, Osadolor OA, Chandolias K, Horvath IS, Taherzadeh, MJ. Innovation pretreatment strategies for biogas production. *Bioresources Technology.* 2016. Available::<https://dx.doi.org/10.1016/j.biortech.2016.11.083>
 25. Abu-Reesh IM. Kinetics of anaerobic digestion of labaneh whey in a batch reactor. *African Journal of Biotechnology.* 2014;13(16):1745-1755.
 26. Juel MAI, Syed SA, Dey TK. Assessment of kinetic coefficients for chrome tannery wastewater treatment by activated sludge system. *Iranica Journal of Energy and Environment.* 2017;8(1):56-60.
 27. Selvabharathi G, Anbarasi K, Ravi SR, Dhanaraja D. Treatment of tannery wastewater by activated sludge process. *Elixir Renewable Energy.* 2017;102:44280-44285.
 28. Abdurahman NH, Rosli YM, Azhari NH. Ultrasonic membrane anaerobic system (UMAS) applications in treating slaughterhouse wastewater. *Australian Journal of Basic and Applied Sciences.* 2015;9(31):79-89.
 29. Sumantri I, Budiyo B, Purwanto P. Kinetic study of anaerobic digestion of ketchup industry wastewater in a three-stages anaerobic baffled reactor (ABR). *Bulletin of Chemical Reaction Engineering & Catalysis.* 2019;14(2):326-335.

© 2020 Nweke and Nwabanne; This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Peer-review history:

*The peer review history for this paper can be accessed here:
<http://www.sdiarticle4.com/review-history/61119>*