JEAS

JOURNAL OF ENGINEERING
AND
APPLIED SCIENCES

Journal of Engineering and Applied Sciences, Volume 18, Number 1, June 2021, 275--286

Anaerobic Digestion of Yam Peel for Biogas Production: A Kinetic Study

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Abstract
The main aim of this study was to evaluate the kinetics of anaerobic digestion of yam peels (YP). 200 ml of water was mixed with 400 g of dried and shredded yam peels and put into 1 L digester. Digestion was carried out for a hydraulic retention time of 15 days. Biogas was collected and measured by downward displacement. The cumulative biogas volume obtained after digestion was 440ml. The first-order, Monod, Contois, and Grau second-order models were applied in the study of the kinetics of the process. Results showed that the first-order model was most acceptable for describing the kinetics of YP digestion with the R^2 value of 0.9636 and constant (K) of 0.0552 day^{-1}. The evaluation of Monod kinetics gave endogenous decay coefficient (K_d), biomass growth yield (Y), the maximum rate of substrate utilization (K_{max}), the half velocity constant (K_S), and maximum specific growth rate of microorganism (μ_{max}) as 0.0042 day^{-1}, 0.0979 mgVSS mgCOD^{-}1, 0.9671 day-^{1}, 182.19 mg/l, and 0.095 day^{-1} respectively. These results showed that inoculation would improve the rate of digestion and biogas production. The Contois model gave μ_{max} and Contois kinetic coefficient (β) values of 0.0098day-^{1} and 3.567 mg COD mgVSS^{-1} respectively. The Grau second-order model was not suitable for simulating the digestion process. The first-order and Monod models gave high R^2>0.9 indicating that these models can be used for designing a batch reactor for the treatment of YP by anaerobic digestion.

Keywords: Anaerobic digestion; Yam peel; Biogas production; Kinetics models

1. Introduction

Most solid wastes are realized from industries, forestry, municipalities, by-products from food, dedicated energy crops, and agriculture (Akwaka *et al*, 2014). These waste materials have either been set on fire, disposed of on land, or buried and dumped on water bodies as forms of disposal. These traditional methods of waste management have reduced the quality of both living things and the environment due to changes in waste composition (Oyegunle, 2016). Currently, the global energy supply relies mainly on fossil fuel sources such as natural gas, oil, and coal, whereas exploits on renewable energy remain at large. Anaerobic digestion is one of the renewable energy sources obtained from biological treatment (Nor-Faekah *et al*, 2020). The energy obtained from treatment by anaerobic digestion has the advantages of being environment-friendly leading to the reduction in the emissions of pollutants and the improvement in energy security in the form of biogas with residue as the end product that could be applied as manure (Rahmat *et al*, 2019). The use of renewable energy will also bring about the creation of local jobs and save the country's expenditure on foreign currency due to fossil fuel importation (Roopnarain & Adeleke, 2017).About 70% of the world's production of yam is obtained from Nigeria and as a result generates more waste from yam peels (Makinde & Odokuma, 2015).

Longjan and Dehouche (2018) reported that Nigeria is the country that produces the largest quantity of yam in the world leading to the unavoidable generation of yam peels that can contribute to serious environmental challenges through unacceptable waste disposal methods. One of the ways of controlling this problem is the use of this food waste to produce renewable energy through anaerobic digestion. Yam tuber peels (*Dioscorea* spp.) are regarded as ordinary waste products but have been observed to be a good source of energy (Longjan & Dehouche, 2018; Afolabi *et al*, 2012). Kinetic models can be applied to evaluate the effectiveness in degrading the organic matter by the bacteria based on the substrate consumption of a substrate during digestion. Kinetics can also be applied in designing and the operation of a digester, and the prediction of their performance (Shete & Shinkar, 2014).

Information needed for the design of full-scale biodigesters and their efficiency when used under the same operating conditions can be estimated from the results of kinetic studies obtained (Nor-Faekah *et al*, 2020).

2.0 Material and methods

2.1 Experimental procedure

A one-liter capacity batch anaerobic digester was connected to a 500 ml measuring cylinder placed upside down in a bowl (downward displacement method) and held steady with the help of a retort stand to calculate the displacement of the water by the biogas. The digester maintained a 600 ml working volume. Yam peels were collected from restaurants at the temporary site of Nnamdi Azikiwe University, Awka. The peels were sun-dried and ground and the substrates were stored at room temperature until use. The homogeneity of the mixture of yam peel and distilled water was maintained by stirring the content manually with a glass stirring rod before using a rubber cap to close it tightly and kept for observation. The content was stirred manually and regularly during the experiment and the setup was observed for the production of biogas until production ceased. Some quantity of the waste was periodically collected during the period of retention from a pipe attached to the digester and analyzed for pH, TSS, COD for kinetic analyses using standard methods (APHA,1995). The kinetic evaluation was done using Microsoft excel (2010 version).

2.2 Kinetic study

2.2.1 First-order kinetic model

The limited substrate consumption is a first-order reaction (Emembolu *et al*, 2017). It indicates the substrate concentration profile with hydraulic retention time (HRT) and expressed as:

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

Where S = Substrate concentration

t = hydraulic retention time (HRT)

K_r = the rate constant

Equation (1) represents an exponential growth and rearranged as (2) below (Khan *et al*, 2016; Abdul *et al*, 2013):

$$S_e = S_o \exp(-K_{fo} t) \qquad (2)$$

Where S_e = the effluent substrate concentration (mg/l)

S_o = the influent substrate concentration (mg/l),

t = the hydraulic retention time (day)

Equation (2) showed that substrate utilization is an exponential growth of the organisms. Taking the natural logarithm of both sides of equation (2) gives equation (3) (Emembolu *et al*, 2017; Nwabanne *et al.*, 2012):

$$ln\left(\frac{S_e}{S_o}\right) = -K_{fo} t \qquad (3)$$

where K_{fo} = the first-order inactivation rate coefficient (l/day).

The linear plot, $-\ln(S_e/S_o)$against t evaluated the slope as the reaction order of reaction with the regression coefficient.

2.2.2 Monod kinetic model

In the Monod kinetic model, the rate of substrate utilization (U) is expressed in terms of effluent substrate concentration (S_e) as

$$\frac{1}{U} = \frac{K_S}{K}\frac{1}{S_e} + \frac{1}{K} \qquad (4)$$

The values of K and K_s were obtained from a linear plot of $1/U$ against $1/S_e$ with the slope and intercept as K_s and K respectively

where $U = \frac{dS/dt}{X}$ = Specific rate of substrate utilization (mg COD/L/day)

K= maximum rate of substrate utilization (day^{-1})

K_s= half-velocity constant/saturation constant (mg/l)

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

'K' value is used to determine the volume of biological reactors because the reactor size reduces as the value of K increases, making the bioreactor design easier (Haydar and Aziz, 2009).K_s evaluated the change in the specific growth rate of bacteria with a change in the concentration of the growth-limiting substrate (Haydar and Aziz, 2009).

The specific rate of substrate utilization is related to mean cell residence time as shown in (5) (Darwin and Fazil, 2018; Abdurahman *et al*, 2015).

$$\frac{1}{\theta} = YU - K_d \qquad (5)$$

θ for batch reactors was evaluated by Nweke & Nwabanne (2014) and Nwabanne *et al* (2012; 2009) as,

$$\theta = \frac{X}{dX/dt} \qquad (6)$$

Where U= the specific rate of substrate utilization

θ = the mean cell residence time (day)

Y= the biomass yield/microbial growth yield (mgVSS mgCOD^{-1})

K_d = endogenous decay coefficient (day^{-1})

A linear plot $1/\theta$ was plotted against $U$was used to evaluate biomass yield (Y) and endogenous decay coefficient (K_d). Y estimated the total amount of sludge production resulting from anaerobic digestion and defined the mass of new cells produced per unit of substrate utilized or removed by the microorganisms present in the treatment system (Nor-Faekah *et al*, 2020). K_d evaluates the net amount of sludge production, giving information on the capacity and cost of the sludge handling facilities because the sludge production and sludge handling facilities become smaller with increasing values of Y and K_d (Nor-Faekah *et al*, 2020; Haydar and Aziz, 2009).

The maximum specific growth rate of microorganism, μ_{max} ,is related to the specific rate of substrate utilization and determined from (7) as

$$K_{max} = \frac{\mu_{max}}{Y} \qquad (7)$$

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

K_{max} = maximum rate of substrate utilization (day^{-1})

This growth occurs as the maximum substrate utilized equals the maximum rate of bacterial growth. μ_{max} indicates the maximum growth rate of microorganisms at the maximum rate at which the substrate is being used up (Bhunia and Ghangrekar, 2008).

2.2.3 Contois kinetic model

The Contois model is similar to the Monod model in that it expresses the relationship between the rate-limiting substrate concentration and the specific growth rate (Jijai *et al*, 2016; Isik and Sponza, 2005) as

$$\mu = \frac{\mu_{max} S}{\beta X + S} \qquad (8)$$

where

$$\mu = \frac{1}{\theta_c} + K_d \qquad (9)$$

Substituting Equation (8) into (9)

$$\frac{\mu_{max} S}{\beta X + S} = \frac{1}{\theta_c} + K_d \qquad (10)$$

The rate of change of substrate concentration (dS/dt) is negligible under the conditions of steady-state, and Equation (11) is obtained.

$$\frac{S_o - S}{\theta_H} = \frac{X}{Y}\left(\frac{1}{\theta_c} + K_d\right) \qquad (11)$$

Rearranging Equation (11), Equation (12) is obtained.

$$\frac{S_o - S}{\theta_H X} = \frac{1}{Y\theta_c} + \frac{K_d}{Y} \qquad (12)$$

The kinetic parameters, Y, and K_d are obtained from the slope and intercept of the linear plot of Equation (5) or (12). 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 (13)

$$\frac{\theta_c}{1 + \theta_c K_d} = \frac{\beta}{\mu_{max}} \frac{X}{S} + \frac{1}{\mu_{max}} \qquad (13)$$

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)

2.2.4Grau second-order kinetic model

The Grau second-order kinetic model has its general equation shown in Equation (14) (Nor-Faekah *et al*, 2020),

$$-\frac{dS}{dt} = k_2 X \left(\frac{S_e}{S_o}\right)^2 \qquad (14)$$

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

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

S_o = Influent substrate concentration(mg/l)

S_e = Effluent substrate concentration (mg/l)

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

Equation (14) is simplified and linearized to become,

$$\frac{S_o \times HRT}{S_o - S_e} = HRT + \frac{S_o}{k_2 X} \qquad (15)$$

$S_o - S_e/S_o$ is known as the substrate removal efficiency (E) and S_o/k_2X is a constant known as 'a'. So, the equation for the plot is given below as

$$\frac{HRT}{E} = a + bHRT \qquad (16)$$

Where the kinetic constants a (day^{-1}) and b (dimensionless) are the intercept and slope determined from the plot of $\frac{HRT}{E}$against HRT respectively. The value k_2 is obtained by inserting the values of S_o and X into $\frac{S_o}{k_2 X}$ (Nor-Faekah*et al*, 2020).

3.0 Results and Discussions

3.1The production of biogas

The effect of hydraulic retention time on both daily and cumulative biogas volumes was observed as YP was anaerobically digested. The plots of daily and cumulative biogas volumes are shown in Figures 1 and 2 respectively. The cumulative biogas volume of YP was 440 ml.The daily biogas production rate for the substrate during the 15-day HRT was observed to increase to a maximum before reducing towards the end of digestion as described by Echiegu (2015).

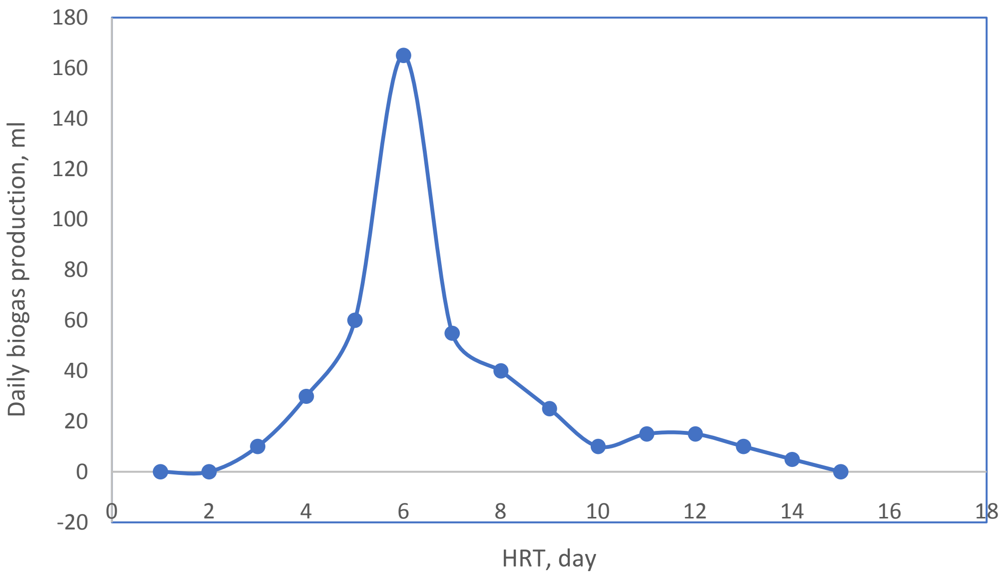

Figure 1: Daily biogas volume with HRT on YPdigestion

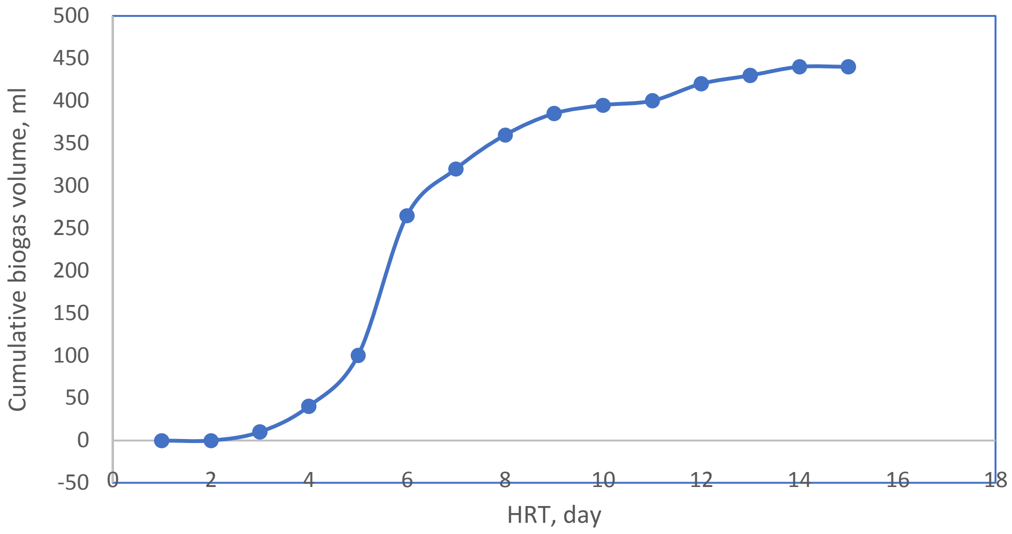

Figure 2: Cumulative biogas volume with HRT on YP digestion

3.2Kinetic analysis

3.2.1First-order kinetic model

The plot of $-\ln(S_e/S_o)$ versus t which was applied for the determination of the first-order kinetics of YP digestion is shown in Figure 3. The kinetic data for the first-order modeling of YP digestion is shown in Table 2. The straight-line plot gave a high coefficient of determination of 0.9638 showing that YP digestion kinetics followed the first-order reaction. The first-order inactivation rate coefficient (*K*) was 0.0552 day^{-1}. The first-order reaction was also reported in Darwin and Fazil (2018).

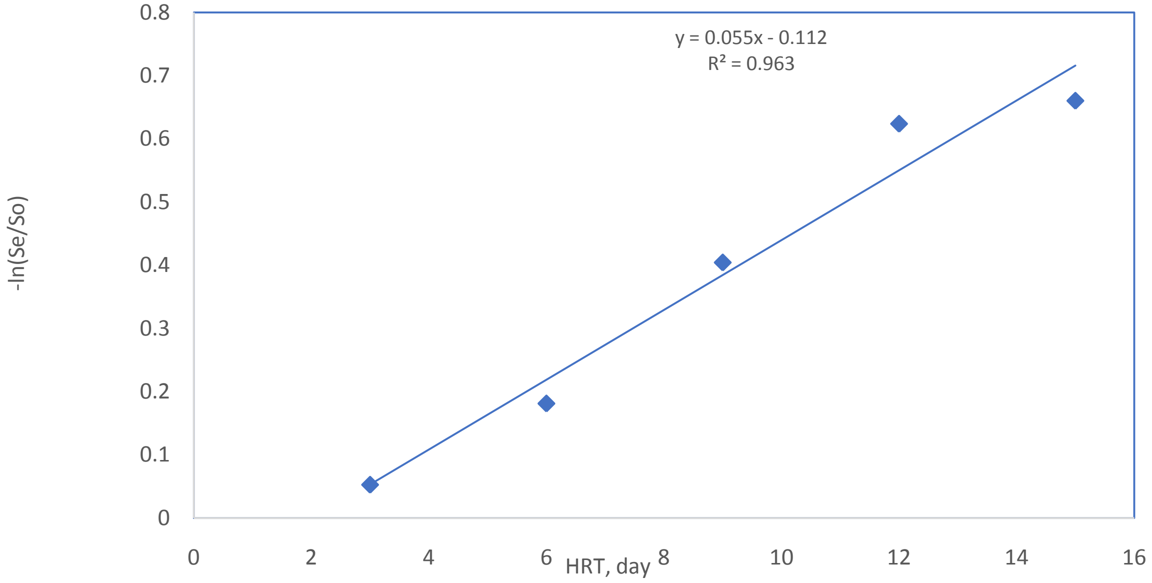

Figure 3: Plot for determination of *K* in First-order kinetic model for YP digestion

3.2.2Monod kinetic model

Table 2 showed the Monod kinetic data for YP digestion. A linear plot of $\frac{1}{U}$ against $\frac{1}{S_e}$ was used to determine $\frac{Ks}{K}$ and $\frac{1}{K}$ as slope and intercept respectively as seen in Figure 4. The reaction constant, K (maximum rate of substrate utilization) wascalculated as 0.9671 day^{-1}. This is the constant rate at which the available food was digested by the microbes before they became inactive. The value of K was small indicating that the retention time required by the microbes to regenerate after being inactivated would be high. Hence, an inoculant would be needed to reduce the retention time required for digestion and the requirement of a large digester to contain both inoculant and waste for effective digestion and improved biogas production (Emembolu *et al*, 2017; Haydar and Aziz, 2009). The value of 182.19 mg/l showed that the concentration of the growth-limiting substrate changed as the bacterial specific growth rate was reduced (Haydar & Aziz, 2009). High K_s value results in increased biodegradability of substrates (Nor-Faekah *et al*, 2020). The plot for evaluating the values of Y and K_d from the Monod kinetics study of YP digestion is shown in Figure 5.A linear graph was obtained by plotting$1/\theta$against U. From the slope and intercept, Y and $K_d$were calculated as 0.0979 mgVSS mgCOD^{-1} and 0.0042 day^{-1} respectively. The low values of the decay coefficient, K_d and biomass yield, Y, obtained indicated that the net sludge volume obtained from the digestion process was low. This is an indication that the size of sludge handling facilities would be small (Nor-Faekah *et al*, 2020; Haydar & Aziz, 2009).

The equation of μ_{max} (obtained from the multiplication of the maximum rate of substrate utilization and biomass yield) showed that the Michaelis-Menten equation linked the consumption of substrate with the bacterial specific growth rate. The values of μ_{max} and K highly depended on the organism and the substrate digested. This maximum specific growth rate occurs when the maximum rate of bacterial space growth equals the maximum substrate consumed (Nor-Faekah *et al*, 2020). μ_{max} for YP was calculated as 0.095 day^{-1}. The low value of μ_{max} implied that the maximum specific growth rate of microorganisms per day was relatively low. It also suggested that the amount of biomass in the digester high (Abdurahman *et al*, 2015). Darwin and Fazil (2018) reported a high value of μ_{max} after studying the Monod kinetics of the anaerobic co-digestion of cow manure and cocoa husk and suggested that the presence of the cell mass of microbes in the digester was low since the concentration of microbial cell mass (K) was inversely proportional to the specific microbial growth rate as anaerobic digestion process took place. The coefficients of determination from Monod kinetic plots for YP digestion were high. This indicated that the first-order and Monod model could be used to describe the digestion process.

Table 1: Analyses for First-order and Monod Kinetics Study on YP 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	5.38	102.36		58.0		0	0
3	4.74		97.11		40.0	10	10
6	4.06		85.40		39.1	155	165
9	4.28		68.33		27.4	220	385
12	3.94		54.87		13.5	35	420
15	3.75		52.91		9.4	20	440

3.2.3 Contois kinetic analysis

The constants of the kinetic equation, β and μ_{max} were evaluated from the Contois plot for YP digestion is shown in Figure 6. The kinetic parameters were evaluated from the slope and intercept after plotting Equation (13) respectively. The values of Y and K_d were 0.0979 mgVSS mgCOD^{-1} and 0.0042 day^{-1} respectively. This value of $K_d$is within the values obtained by Jijai *et al* (2016). The values of constants,μ_{max} and β were calculated as 0.098 day^{-1} and 3.567 mgCOD mgVSS^{-1} respectively. The μ_{max} value obtained from the Contois model was close to the μ_{max} value from the Monod model (0.095 day^{-1}) in this study. The similarity in μ_{max} value evaluated from both Contois and Monod models in the kinetics of YP digestion was also observed between the Contois and Monod models from the kinetics of the substrates studied in Jijai *et al* (2016) and Isik and Sponza (2005). The low value of μ_{max} in the Contois model of this study signified a decrease in the substrate removal rate. Besides, the difference in μ_{max} values are mainly because reactor configurations significantly vary in different studies (Isik and Sponza, 2005). The value of β in this study was high which is a result of a strong negative effect of the granular size of YP which reduced the accessibility of the microbial cells (Jijai *et al*, 2016). In conclusion, the kinetic study with the use of the Contois model was less suitable than the Monod model for YP digestion due to the lower R^2 value of 0.7893 obtained.

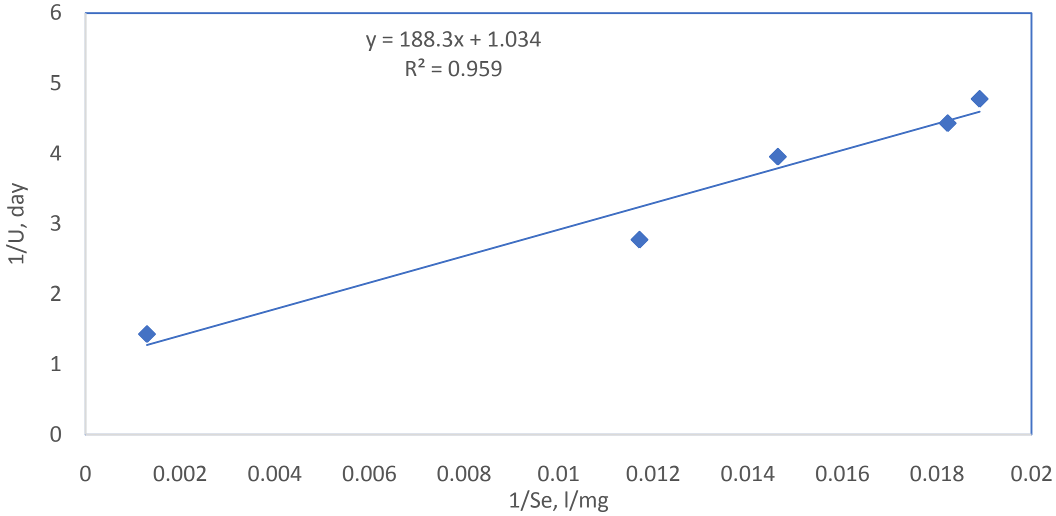

Figure 4: Plot for the evaluation of K and K_s in Monod model for YP digestion

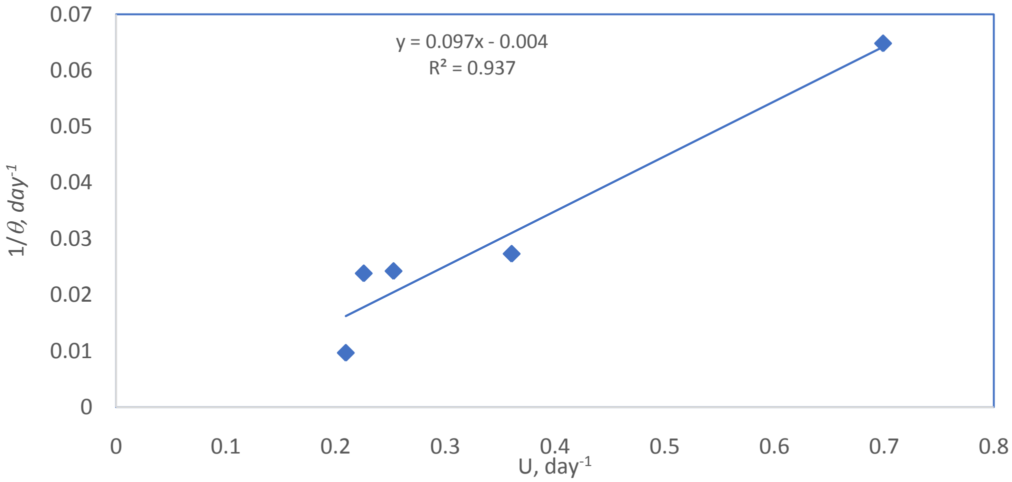

Figure 5: Plot for determination of Y and K_d in Monod model for YP digestion

3.2.4 Grau second-order kinetic analysis

The parameters evaluated from the Grau Second-order model are shown in Table 2 while the plot is presentedin Figure 7. It can be seen from the correlation coefficient (R^2) that the anaerobic digestion of YP did not follow the second-order reaction. This was contrary to the results obtained by Gnanapragasam *et al* (2017) where high R^2 value was obtained from predicting the performance of treating the combination of real textile dyeing and sago wastewater with a two phase hybrid UASB reactor.Table 3 showed the kinetic parameters obtained from the four kinetic models.

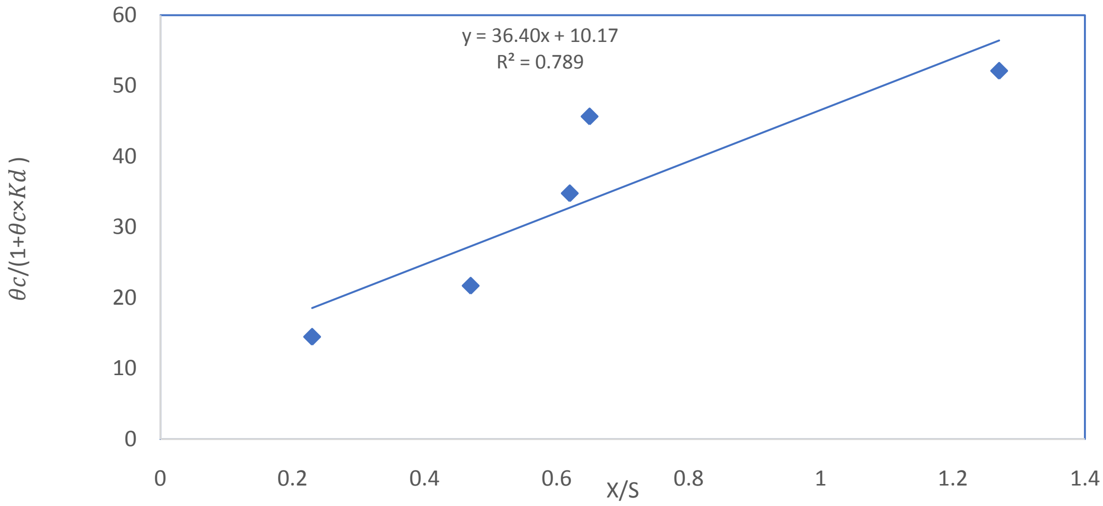

Figure 6: Plot for determination of μ_{max} and β in Contois model for YP digestion

Table 2: Data for Grau second-order Kinetics Study on YP 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	102.36	-	-	-
3	102.36	97.11	5.13	58.49
6	102.36	85.40	16.57	36.21
9	102.36	68.33	33.25	27.07
12	102.36	54.87	46.40	25.86
15	102.36	52.91	48.31	31.05

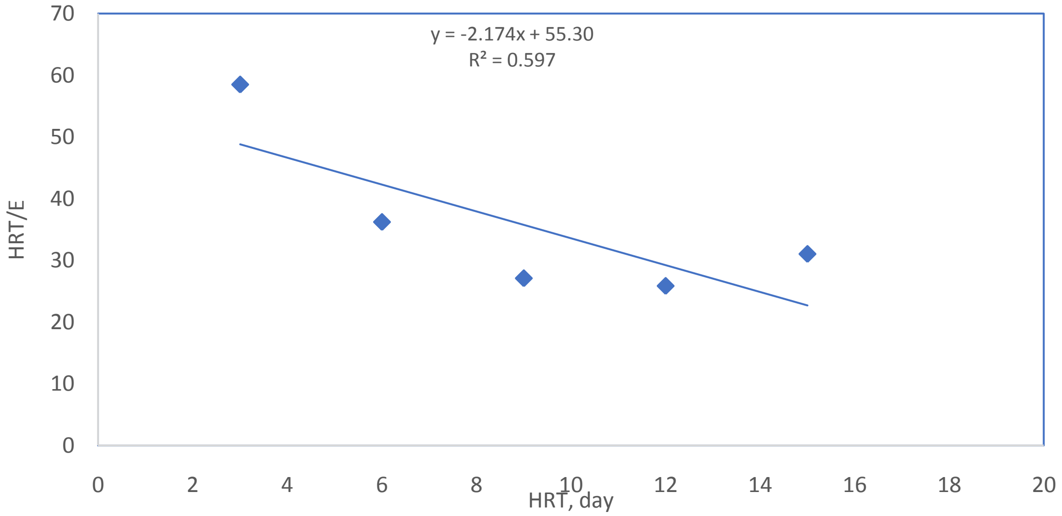

Figure 7: Plot for determination of *a, b*and *k* for Grau second-order model for YP digestion

Table 3: Kinetic Parameters of Anaerobic Digestion of YP

Kinetic models	Kinetic parameters	Values	Regression coefficient (R^2)
First-order	K (day^{-1})	0.0552	0.9636
Monod	K (day^{-1})	0.9671	0.9598
	K_s (mg/l)	182.19	0.9598
	Y (mgVSS mgCOD^{-1})	0.0979	0.9371
	K_d (day^{-1})	0.0042	0.9371
	μ_{max} (day^{-1})	0.0095	-
Contois	Y (mgVSS mgCOD^{-1})	0.0979	0.9371
	K_d (day^{-1})	0.0042	0.9371
	μ_{max} (day^{-1})	0.0098	0.7893
	β (mgCOD mgVSS^{-1})	3.567	0.7893
Grau second-order	a (day^{-1})	55.305	0.5971
	b	-2.174	0.5971

As seen from the results, the first-order and Monod models provided high coefficients of determination. These models are capable of predicting the behavior of the batch digester used in the treatment of yam peel waste (Mekonnen *et al*, 2017). However, the first-order model had the highest regression coefficient. This result proved that the model was most suitable for predicting COD effluent as indicated by higherregression coefficient (Jijai *et al*, 2015).There were few differences between the constants obtained from Monod and Contois models as seen in other studies (Jijai *et al*, 2015).The values of the kinetic constants determined from the models applied in this study werenot comparable to other studies because the substrate concentration used in this studywas lower than those of most previous studies(Jijai *et al*, 2015). The data generated from this study can be used in the design of a batch digester for the anaerobic digestion of only wastes with low substrate concentration like yam peels. Grau second-order model could not be used to predict the performance of digesting yam peels anaerobically with a batch digester. This result was observed to be contrary to Mekonnen *et al* (2017) were Grau second-order was most successful in modeling the experimental results obtained from treating tannery wastewater due to the high correlationcoefficient obtained whereas the first-ordermodel was least successful.

4.0. Conclusion

Four kinetic models were used for the kinetic study of YP digestion. The first-order kinetic constant (K) was 0.0552 day^{-1}. The Monod kinetic parameters K,K_s, Y, K_d and μ_{max} obtained were 0.9671 day^{-1}, 182.19 mg/l, 0.0979 mgVSS mgCOD^{-1}, 0.0042 day^{-1}and 0.0095 day^{-1}respectively. The constants ofMonod kinetics showed that the digestion of YP needed inoculation and hence, a large digester for optimum biogas production. The coefficients of determination from the first-order and Monod kinetic plots for YP were high indicating the ability of the kinetic models in evaluating the digestion process. However, the first-order kinetic model best described the kinetic study when considering the value of the determination coefficient.

5.0 Recommendation

This study can be applied as a solution for the unhealthy disposal of yam peels in developing countries, including Nigeria, where their disposal without treatment causes environmental pollution. The evaluation of anaerobic digestion of yam peels under field conditions using pilot-scale studies can also be carried out to obtain the necessary data required for a full-scale design.

Nomenclature

APHA = American Public Health Association
COD = Chemical Oxygen Demand
HRT = Hydraulic Retention Time (day)
K_r = the rate constant

K_{fo} = the first-order inactivation rate coefficient (l/day)
K_{max} = maximum rate of substrate utilization (day^{-1})
K_d = Endogenous Decay Coefficient (day^{-1})
K_s = Half-velocity constant, mg/l
S_o = COD value 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)
YP = Yam peel
$\theta = \frac{X}{dX/dt}$ = The mean cell residence time (day)
$\square_{max}$ = Maximum Specific Growth Rate of Microorganisms (day^{-1})

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