Kinetic Modeling of Anaerobic Digestion of Restaurant Waste Water

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Authors' contributions

This work was carried out in collaboration between all authors. Author LNE carried out the practicals with author OCE. Author JTN did the literature and discussion section. Authors LNE and OCE did the statistical analysis. All authors proof read the work and approved it for publication.

Original Research Article

ABSTRACT

This work presents the treatment of Restaurant wastewater using anaerobic digestion technique. The physicochemical analysis revealed that most of the wastewater parameters were reduced after digestion to an acceptable level. The bio-kinetics of the anaerobic digestion was well described by the first-order kinetic model. The kinetic parameters calculated for the batch digestion process were 0.0494 day^{-1} for K, 108.96 mg/l for K_s, 0.0282 day^{-1} for K_d, 1.5886 mg/mg for Y and 0.0789 day^{-1} for μ_{max}. The kinetics of the biomass growth and substrate utilization rate together with the kinetic data obtained were used to develop a mathematical model for a continuous flow reactor unit under homogeneous steady state condition. As the food to micro-organism ratio increased, there was a decrease in the biomass concentration and an increase in the hydraulic retention time. The developed design data can be used in the design of the continuous process plant.

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1. INTRODUCTION

Food waste is a growing issue, and the disposal of it is controversial, given increased food prices and the resources required. The food waste includes uneaten food and food preparation leftovers from residences, commercial establishments such as restaurants, institutional sources like school cafeteria, and industrial sources like factory lunchrooms. When discharged, these wastes constitute great danger to the environment. In several cases, rivers and lakes have become recipients of large quantities of putrescible organic substances far exceeding their natural purifying capacities resulting in the deterioration of water supplies and far reaching economic and health consequences [1]. To combat this increasing burden on our aquatic environment, increasingly strict regulation on pollution discharge is being implemented by various governmental bodies, with focus primarily on waste reduction [2]. On initial discharge, these wastewaters can contain high levels of inorganic pollutants which can be easily biodegradable, but whose impact load on the ecosystems, either in Total Suspended Solids (TSS), Biochemical Oxygen Demand (BOD5), or Chemical Oxygen Demand (COD), may be in the tens of thousands mg/L. Drinking water sources are often threatened by increased concentration of pathogenic organisms as well as by numerous new toxic chemicals disposed by industry and agriculture sector [1]. To combat this increasing burden on our aquatic environment, increasingly strict regulation on pollution discharge is being implemented by various governmental bodies, with focus primarily on waste reduction [2].

There are many biological and physiochemical treatment methods of removing wastewater pollutants [3]. However, the best environmentally practicable option is the conversion of waste components to energy, fuels and other valuable products, as well as the recovery or salvage of existing materials [4]. Though there are other techniques that can be used to treat this waste, anaerobic digestion has been one of the oldest and most common methods for sludge management, due to its potential for stabilization of large volume of sludge at a low cost no oxygen requirement, low biomass production, high destruction rate of pathogens and generation of methane as an energy source [5].

The advantages of the anaerobic digestion process include less energy requirement, less biological sludge production, small reactor volume, methane production etc. Hence, the anaerobic digestion process is a potential energy source as seen with the biogas production.

Biogas is a renewable source of energy which can relieve the burden of dependence on fossil fuels [6]. The storage, transportation and distribution of biogas are cheap and economical; their handling less hazardous than that of fossil fuels [7].

Among the various operational parameters that influence the anaerobic digestion process of wastewater, the most important ones are the mass of the organic substrate, moisture content, reaction temperature and the amount of biomass available [8].

Their kinetic analysis result can be used to estimate treatment efficiencies of full scale reactors with the same operational conditions [9]. In order to be able to design, predict how the system responds to changes in feed conditions and operate efficiently under anaerobic conditions, appropriate mathematical models need to be developed [10]. [11] and [12] developed kinetic models for the gas generation of the anaerobic digestion and for the anaerobic digestion of MSW respectively by considering Monod's kinetics of biomass growth and substrate utilization. It was applied to estimate the time required for a batch digestion process.

In this present work, both the batch anaerobic digestion of Restaurant wastewater and a mathematical model for the continuous flow anaerobic digestion process is being discussed. The effects of the substrate and biomass concentration on the efficiency and influent substrate concentration were determined which can be used to determine the hydraulic retention time (HRT) and the solid retention time (SRT).

2. MATERIALS AND METHODS

2.1 Wastewater Sample Collection

Restaurant wastewater was collected from a restaurant in Ogbete main market, Enugu state, Nigeria. They were stored in three 20 litre containers.

2.1.1 Experimental procedure

The anaerobic batch digester was set up with 18 liters of the wastewater poured into the digester to enable an extra space for gas collection at the top of the digester. The content was stirred thoroughly before being sealed with the air tight lid and kept for observation. It was stirred thoroughly on daily basis by carefully shaking the digester to ensure intimate contacts of the wastewater with microorganisms responsible for converting the wastewater to biogas. During the digestion, wastewater temperature was recorded periodically.

The pH of the wastewater was taken after every five days to ensure stability of the wastewater slurry. During the retention period, some quantity of the wastewater was collected from an outlet in the digester tightly sealed and only provided for periodic collection of sample for COD_5, BOD and TSS analysis.

Biogas production was monitored periodically until gas production became negligible. A valve in the cone head of the digester was used for daily collection of biogas. Biogas production was measured by downward displacement of water in the measuring cylinder and recorded as the difference between the initial reading at the beginning of each day and the final reading at the end of that same day. Microbial load of the wastewater slurries were determined every five days, from the point of charging to the end of the retention period.

2.1.1.1 Batch kinetic study

The kinetics of the microbial process of anaerobic digestion may be divided into kinetics of growth and kinetics of food (or substrate) utilization [13]. The COD was determined using a time-average cell mass. The limited substrate consumption can be expressed as:

$$-ds/dt = k_1 S \qquad (1)$$

Integrating equation (1) with respect to t from S to S_o and from t to 0 give:

$$S = S_0 \exp(-k_1 t) \qquad (2)$$

Where S_o is the initial influent substrate concentration (mg/l), s is the effluent substrate concentration (mg/l), K_1 is the first order inactivation rate constant (l/day) and t is time (days).

Equation (2) describes an exponential profile of the substrate growth. Rearranging and taking natural logarithm;

$$\ln\left[S/S_0\right] = -k_1 t \qquad (3)$$

This is a first-order reaction kinetics which is used to verify the kinetics of the process. When the plot of $-\ln (S/S_o)$ against t gives a straight line with appropriate regression coefficient, then the process is said to have followed the first-order kinetics model. The slope of the straight line will be used to evaluate the first-order inactivation rate constant (l/day).

The maximum rate of substrate utilization (K) is obtained by using the relationship between the rate of substrate utilization (U) and the effluent substrate concentration (S_e).

$$1/U = K_S/KS_e + 1/K \qquad (4)$$

Where K_s is half-velocity constant (mg/l).

The linear plot of 1/U against $1/S_e$ is used to determine the constants K and K_s from the intercept and slope of the graph. These values indicate whether there is need for inoculation in the system.

The relation between the mean cell residence time (Ѳ) and the specific rate of substrate utilization (U) is given by;

$$1/\theta = YU - K_d \qquad (5)$$

From the plot of 1/ Ѳ against U, the biomass yield (mg/mg) Y and the endogenous decay coefficient (day^{-1}) K_d can be evaluated from the slope and intercept of the linear plot respectively.

The maximum specific rate of micro-organism growth μ_{max} is calculated using;

$$K = \mu_{max}/Y \qquad (6)$$

Where Y is the biomass yield and K is the maximum rate of substrate utilization.

2.1.1.2 Continuous process design model

The characteristics of continuous mode reactor are completely different because the substrate concentration approaches constant under steady

state condition [8]. For continuous reactor under steady state, the rate of substrate utilization is:

$$-ds/_{dt} = (S_0 - S)/_\theta \qquad (7)$$

Where Ɵ is the hydraulic retention time (HRT).

The rate of increase of the biomass concentration X is modelled as a first-order process

$$dx/_{dt} = \mu X \qquad (8)$$

Where μ = specific growth rate (day^{-1})

Monod discovered in 1949 that the limiting substrate concentration, S is related to μ as follows

$$\mu = \mu_{max}\left[S/_{(K_s + S)}\right] \qquad (9)$$

Where μ_{max} is maximum specific growth rate of micro-organism (day^{-1}).

Combining equations (8) and (9) gives:

$$dx/_{dt} = \mu_{max}\left[XS/_{(K_s + S)}\right] \qquad (10)$$

Given the biomass yield coefficient as Y, the relationship between the rate of substrate utilization and the rate of biomass growth is given by:

$$dx/_{dt} = -Y\left(ds/_{dt}\right) \qquad (11)$$

Substituting equation (10) into equation (11) gives:

$$\mu_{max}\left[XS/_{(K_s + S)}\right] = -Y\left(ds/_{dt}\right) \qquad (12)$$

If maximum rate of substrate utilization $K = \frac{\mu_{max}}{Y}$, then rearranging equation (12) gives

$$-ds/_{dt} = KXS/_{(K_s + S)} \qquad (13)$$

For continuous homogenous reactor under steady state will involve incorporating equation (7) into equation (13) to yield

$$S_0 - S/_\theta = KXS/_{(K_s + S)} \qquad (14)$$

If E is the efficiency of the reactor, the substrate concentration at the retention time is

$$S = S_0(1 - E) \qquad (15)$$

Substituting this into equation (14) and rearranging gives the hydraulic retention time Ɵ, as

$$\theta = ES_0[K_s + S_0(1 - E)]/_{KXS_0(1 - E)} \qquad (16)$$

The solid retention solid (SRT) of the anaerobic digestion is given by:

$$\theta_s = X/_{-Y\, ds/_{dt} - K_d X} \qquad (17)$$

For continuous homogenous reactor under steady state, equation (17) becomes

$$\theta_s = X/_{-Y\left[(S_0 - S)/_\theta\right] - K_d X} \qquad (18)$$

At any particular efficiency E, the SRT becomes

$$\theta_s = X/_{Y\left(ES_0/_\theta\right) - K_d X} \qquad (19)$$

3. RESULTS AND DISCUSSION

3.1 Characterization and Proximate Analysis

Table 1 shows the result of the physicochemical analysis before and after the anaerobic digestion. The temperature fluctuated between 32°C to 29°C. The wastewater became almost neutral to litmus as the pH slightly increased from 6.17 to 6.50 which is within the WHO standards [14]. After the digestion, the calcium decreased from 18.75 to 8.65 ppm, total nitrogen content decreased from 3.06 to 0.498 and sodium level decreased from 2.859 to 0.986 ppm which was also below the maximum acceptable limits of the WHO. The TSS, BOD, TVC and COD were greatly reduced after the digestion period from 700 to 175 mg/l, 1115 to 192, 90 x 10^4 to 80 x 10^2 (CFU/100 ml) and 930 to 250 mg/l respectively but were still not within the WHO acceptable levels. These can still be improved upon by increasing the digestion.

Table 2 is the result of the proximate analysis carried out on the wastewaters slurry after the

digestion. It was observed that the total solid content (85%) was high. A low ash content indicates loss of some minerals during the digestion process. The carbohydrate value of 58.35% was high. This is expected since the restaurant wastewater consists mainly of food wastes among other wastes.

3.1.1 Effect of parameters

Fig. 1 is a plot of the time on the biological oxygen demand (BOD) of the wastewater digestion. It was observed that there was a decrease in the BOD level of the wastewater with time from 1100 mg/l to about 300 mg/l at the end of the digestion. This is mainly because as their food reduced, the micro-organisms that depend on the food start dying off.

Fig. 2 shows the variation of the pH with time on the wastewater. The initial pH was slightly acidic and fluctuated between 6.0 and 9.0 which were within the standard WHO limit. Based on the fact that the pH of the wastewater was almost neutral, it can be discharged into water bodies without the aquatic life being affected adversely.

The effect of time on the cumulative volume of gas produced during the digestion is shown in Fig. 3. It was seen that there was an increase in the quantity of gas produced with time. The gas production can be increased by inoculation. About 30 m^2 of biogas was produced. According to [1], 1.4KWh of energy can be obtained from 1 m^3 of biogas. Therefore about 42 KWh of energy can be obtained from this anaerobic digestion process.

Table 1. Characterization of treated and untreated wastewater

| Parameter	Concentration		
	Before digestion	**After digestion**	**WHO**
pH	6.17	6.50	6.0-9.0
Temperature (°C)	32.0	29.0	–
Total suspended solid (TSS) (mg/l)	700.0	175.0	30.0
Calcium hardness/Water hardness/Bicarbonate (mg/l)	135.0	99.10	–
Sulphate (mg/l)	312.0	224.5	200.0
Total Nitrogen (mg/l)	3.06	0.498	4.0
Total viable count (Fecal Coliform) (cfu/100 ml)	90×10^4	80×10^2	400.0
Biological oxygen demand (BOD_5)	1115.0	192.0	——
Phosphate (mg/l)	1.069	0.634	–
Oil and Grease (%)	265.0	98.9	0.10
Manganese (ppm)	0.00	0.00	0.30
Iron (ppm)	0.789	0.225	0.30
Sodium (ppm)	2.859	0.986	75.0
Potassium (ppm)	0.645	0.153	–
Calcium (ppm)	18.75	8.65	75.0
Magnesium (ppm)	0.00	0.00	–
Aluminum (ppm)	0.251	0.009	–
Chemical oxygen demand (COD) (mg/l)	930.0	250.0	200.0
Zinc (ppm)	14.84	1.450	1.00
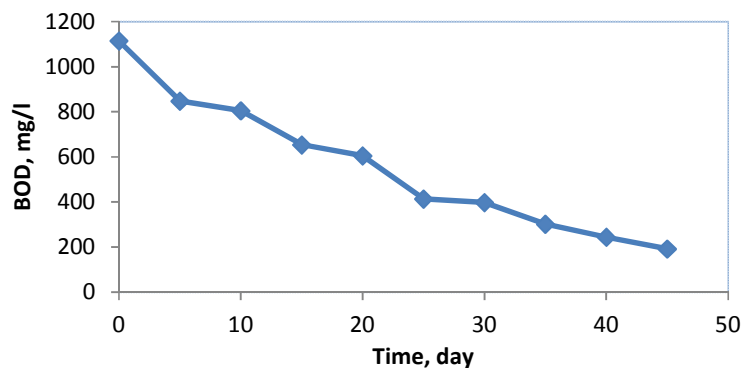
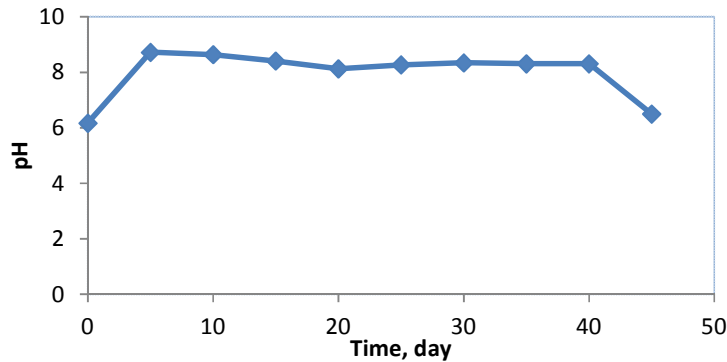**Fig. 1. Effect of BOD with time of the digestion**

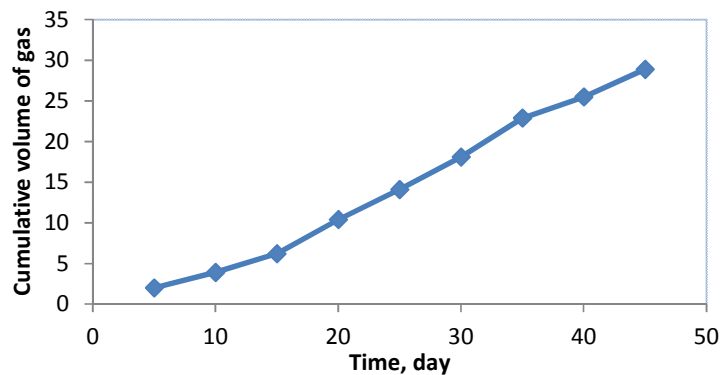**Fig. 2. Effect of pH with time of the digestion**

Fig. 3. Effect of Cumulative volume of gas produced with time

Table 2. Proximate analysis of the wastewater slurry after digestion

Parameter	Percentage composition
Moisture content (%)	15.0
Total solid (%)	85.0
Ash content (%)	20.0
Fat content (%)	1.5
Nitrogen content (%)	0.504
Protein content (%)	3.15
Fibre content (%)	2.0
Carbohydrate content (%)	58.35
Volatile solid (%)	12.5
Carbon content (%)	2.5
C/N ratio	4.96
pH	6.5

The effect of temperature with time of the wastewater digestion is presented in Fig. 4. It is observed that during the period of digestion, the temperature was maintained at the thermophilic level (30 to 40°C) and that it never reached the never reached the mesophilic level (between 40 to 55°C). This is probably because of the nature of the wastewater and that the anaerobic digestion proceeded much more rapidly at that temperature.

3.1.1.1 Kinetics analysis

Table 3 is the result of the batch experimental data that was used to calculate the kinetic parameters.

The plot of $-ln(S_e/S_o)$ versus t was used to analyze the first order kinetic of the anaerobic digestion as shown in Fig. 5. A high correlation coefficient of 0.9777 confirmed that the anaerobic digestion fitted the first-order kinetic. The first-order inactivation rate constant K was obtained as 0.0319 day^{-1} from the slope of the linear plot. The high value of K showed that the rate of decomposition is a function of the concentration of the solid waste and other environmental factors [12].

Fig. 6 was used to determine the maximum rate of substrate utilization K and the half-substrate constant K_s by plotting the linear graph of $\frac{1}{v}$ against $\frac{1}{S_e}$ which gave the slope as $\frac{K_s}{K}$ and the

intercept as $\frac{1}{K}$ from where K was obtained as 0.0494 day^{-1} and K_s was obtained as 108.96 mg/l. The correlation coefficient was 0.9848. Furthermore, the K value was small suggesting that there is need for inoculation in order to

ensure better performance. Some authors such as [12] obtained similar value of 0.038 day^{-1} in the treatment of Municipal waste using anaerobic digestion.
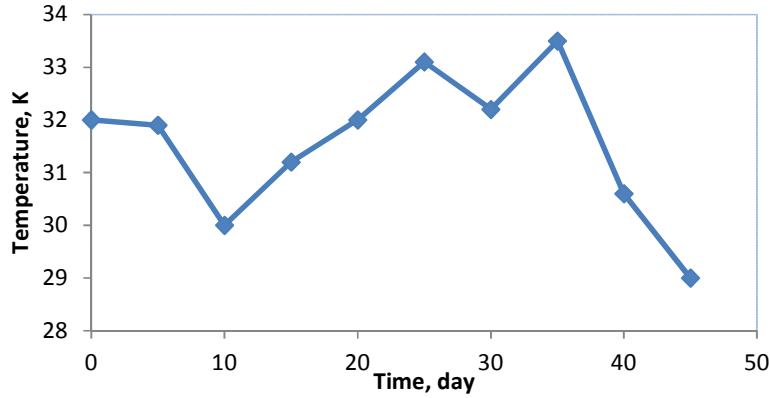

Fig. 4. Effect of temperature with time of the digestion

Table 3. Batch experimental data for determination of kinetic parameters

T (days)	COD (mg/l)	BOD (mg/l)	TSS (mg/l)	TVC (cfu/100 ml)	So (mg/l)	Se (mg/l)	Xo (mg/l)	Xe (mg/l)	X (mg/l)
0	930.0	1115.0	700.0	90×10^4	930.0		700.0		
5	848.0	848.0	667.0	94×10^5		848.0		667.0	683.5
10	805.0	805.0	595.0	106×10^9		805.0		595.0	647.5
15	654.0	654.0	466.0	110×10^9		654.0		466.0	583.0
20	605.0	605.0	409.0	111×10^9		605.0		409.0	554.5
25	414.0	414.0	358.0	102×10^7		414.0		358.0	529.0
30	380.0	398.0	249.0	99×10^5		380.0		249.0	474.5
35	350.0	302.0	209.0	92×10^2		350.0		209.0	454.5
40	299.0	244.0	180.2	89×10^2		299.0		180.2	440.0
45	250.0	192.0	175.0	80×10^2		250.0		175.0	437.5

Xo = Influent total suspended solid TSS in mg/l, Xe = Effluent total suspended solid TSS in mg/l,
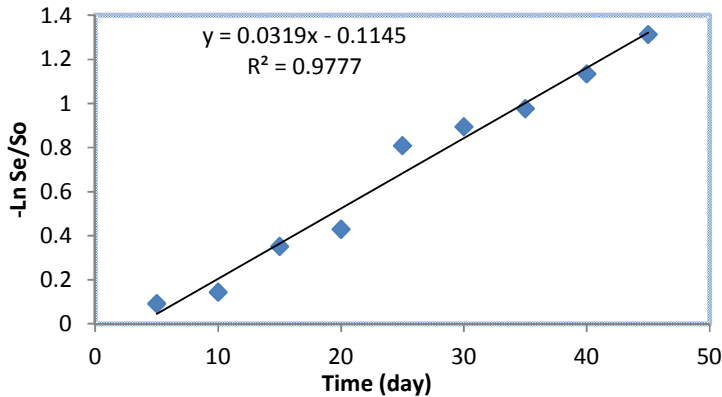*X = Average TSS cell mass concentration*

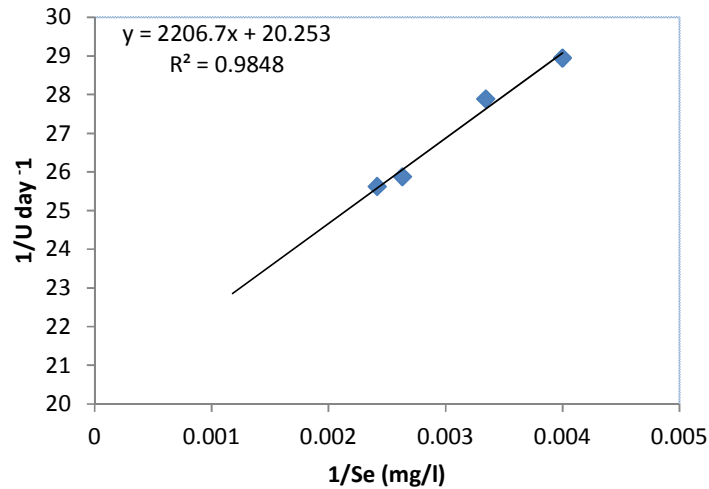**Fig. 5. First order kinetic plot for the anaerobic digestion**

Fig. 6. Plot for determination of K and K_s

The biomass yield, Y and the endogenous decay coefficient K_d were determined by plotting the straight line graph of the inverse mean cell residence $\frac{1}{\theta}$ against the specific rate of utilization, U. Fig. 7 showed that the coefficient of correlation was 0.9873. The values of Y and K_d were obtained from the slope and intercept of the plot as 1.5886 mg/mg and 0.0282 day^{-1} respectively. The value of the K_d obtained was small indicating that the net sludge volume was high, hence the size of the sludge handling facilities would be large [15]. The maximum specific growth rate of micro-organism, U_{max} was calculated to be 0.0789.

3.1.1.2 Continuous process design model simulation

The HRT required in a homogeneous continuous flow type reactor under steady state to accomplish the anaerobic digestion was calculated for different reactor efficiencies (E) of 70 to 90%. The influent COD was 930 mg/l and the food to micro-organism ratio (F/M) used was 0.7, 0.75, 0.8, 0.85, 0.9, 0.95, and 1.0 thus obtaining the corresponding biomass concentration of 1328.6, 1240, 1162.5, 1094.1, 1033.3, 978.9 and 930 mg/l respectively. The values obtained were presented in Table 4 while the graphical plot is in Fig. 8. It was seen that the HRT increased linearly with increase in efficiency of the reactor. Equally, as the F/M ratio increased (and biomass concentration decreased), there was a corresponding increase in the HRT representing a series of parallel line. [8] equally

obtained the same increase as a series of parallel lines.

At the same time, the SRT was calculated for the same homogeneous continuous flow type reactor under steady state for the anaerobic digestion of RW and presented in Table 4. The influent COD was 930 mg/l. Fig. 9 showed that with increase in the reactor efficiency, the SRT increased.

The effect of different influent substrate concentration on the HRT value to attain a targeted efficiency in the homogeneous continuous flow type reactor under steady state condition was studied for the anaerobic digestion of RW. Varying the influent substrate concentration in the range of 1328.6 to 930.02 mg/l using the calculated difference of 56.94 mg/l, the biomass concentration was taken as 1162.5 and 930 mg/l corresponding to the two F/M ratios of 0.8 and 1.0. Reactor efficiencies of 70, 80 and 90% were used for the two F/M ratios. Table 5 showed the values obtained while Fig. 10 showed the variation of HRT with the variation of the influent substrate concentration for the anaerobic digestion of RW. The HRT was seen to increase linearly with increase in influent substrate concentration for a particular value of reactor efficiency and biomass concentration. Equally, for a decrease in biomass concentration and an increase in reactor efficiency, the HRT increases.

Fig. 11 showed the variation of SRT with varying influent substrate concentration for different

values of reactor efficiencies (70, 80 and 90%) corresponding to the two F/M ratios of 0.8 and 1.0. It was observed that there is a decrease in the SRT (about 144h for 70%) with increase in the influent substrate concentration. This indicated that as the efficiency increased, the decrease in SRT becomes more evident. A much slighter decrease of about 11 hours for 90% was reported by Asok et al. 2011 in the treatment of Municipal Solid Wastes.
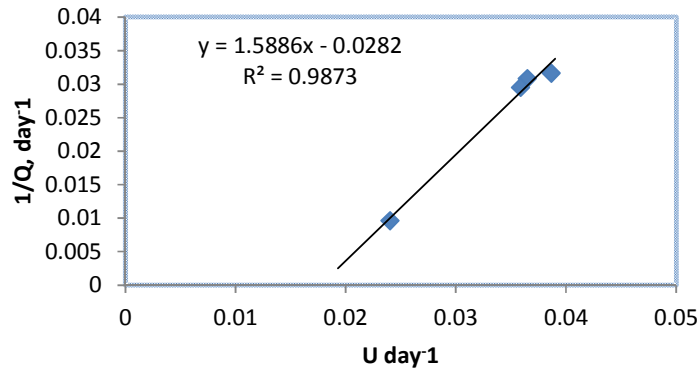

$$y = 1.5886x - 0.0282$$
$$R^2 = 0.9873$$

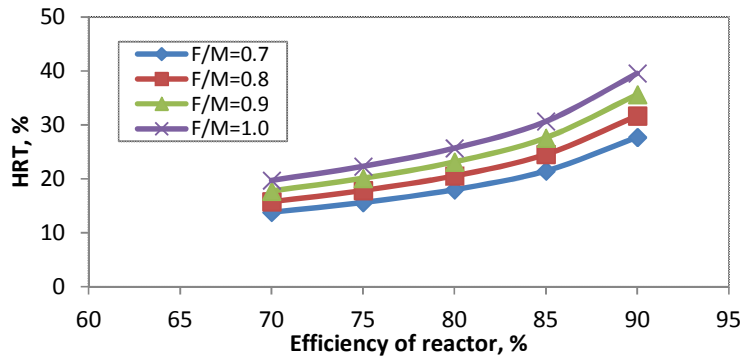**Fig. 7. Plot for determination of Y and K_d**

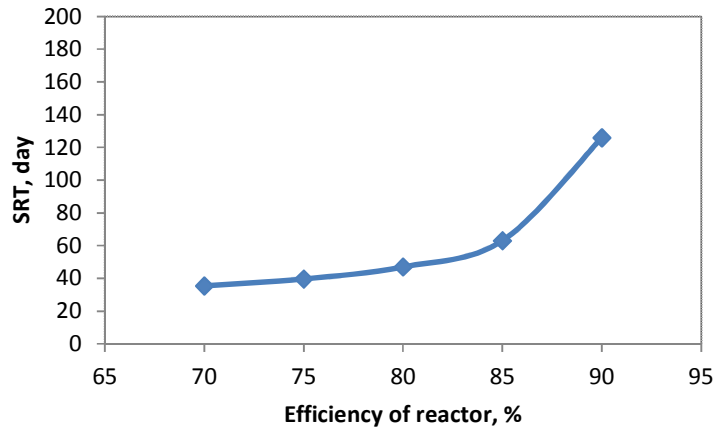**Fig. 8. Variation of HRT with efficiency of the anaerobic digestion**

Fig. 9. Variation of SRT with efficiency of the anaerobic digestion

Table 4. Variation of HRT and SRT with variation of efficiency of anaerobic digestion

Efficiency (%)	Influent COD, S_o (mg/l)	Biomass concentration X (mg/l)							HRT (day)							SRT (day)
		F/M =0.7	F/M =0.75	F/M =0.8	F/M =0.85	F/M =0.9	F/M =0.95	F/M =1.0	F/M =0.7	F/M =0.75	F/M =0.8	F/M =0.85	F/M =0.9	F/M =0.95	F/M =1.0	
70	930	1329	1240	1163	1094	1033	978.9	930	13.79	14.78	15.76	16.76	17.73	18.72	19.70	35.40
75	930	1329	1240	1163	1094	1033	978.9	930	15.61	16.72	17.84	18.95	20.07	21.18	22.30	39.63
80	930	1329	1240	1163	1094	1033	978.9	930	17.98	12.26	20.54	21.83	23.11	24.40	25.68	46.99
85	930	1329	1240	1163	1094	1033	978.9	930	21.45	22.98	24.52	26.05	27.58	29.12	30.65	63.03
90	930	1329	1240	1163	1094	1033	978.9	930	27.69	29.67	31.65	33.63	35.61	37.59	39.56	125.9
95	930	1329	1240	1163	1094	1033	978.9	930	45.00	48.22	51.43	54.65	57.87	61.05	64.29	211.7

Table 5. Variation of HRT and SRT with variation of influent substrate concentration of anaerobic digestion

| Influent COD, S_o (mg/l)	Reactor efficiency (%)			Biomass, X (mg/l)		HRT (day)						SRT (day)		
	E1	E2	E3	F/M =0.8	F/M =1.0	E1 + X1	E1 + X2	E2 + X1	E2 + X2	E3 + X1	E3 + X2	E1	E2	E3
930.02	70	80	90	1163	930	15.76	19.70	20.55	25.68	31.65	39.56	35.40	47.00	125.95
986.96	70	80	90	1163	930	16.46	20.57	21.34	26.67	32.54	34.29	34.29	44.72	109.85
1043.9	70	80	90	1163	930	17.15	21.44	22.13	27.66	33.44	33.30	33.30	42.79	98.10
1100.84	70	80	90	1163	930	17.86	22.31	22.92	28.66	34.33	32.51	32.51	41.14	88.98
1157.78	70	80	90	1163	930	18.54	23.17	23.72	29.65	35.22	31.71	31.71	39.74	81.77
1214.72	70	80	90	1163	930	19.23	24.04	24.51	30.64	36.11	31.03	31.03	38.49	75.92
1271.66	70	80	90	1163	930	19.90	24.91	25.30	31.63	37.01	30.37	30.37	37.38	71.13
1328.6	70	80	90	1163	930	20.62	25.78	26.10	32.62	37.90	29.91	29.91	36.43	67.05
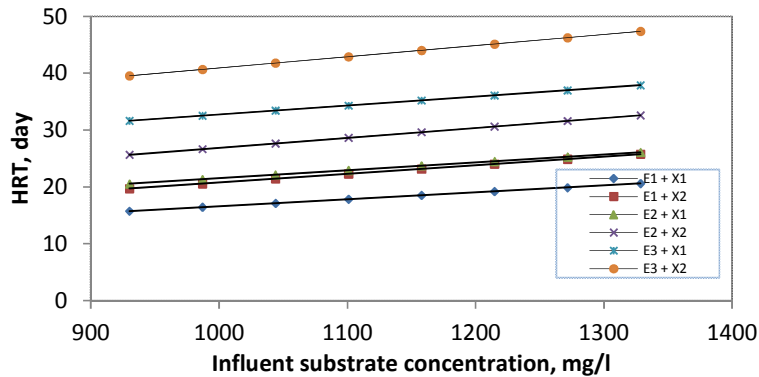
Fig. 10. Variation of HRT of anaerobic reactor with influent substrate concentration (*E1*=70%, *E2*=80%, *E3*=90%, *XI*=1163 mg/l, *X2*=930 mg/l)
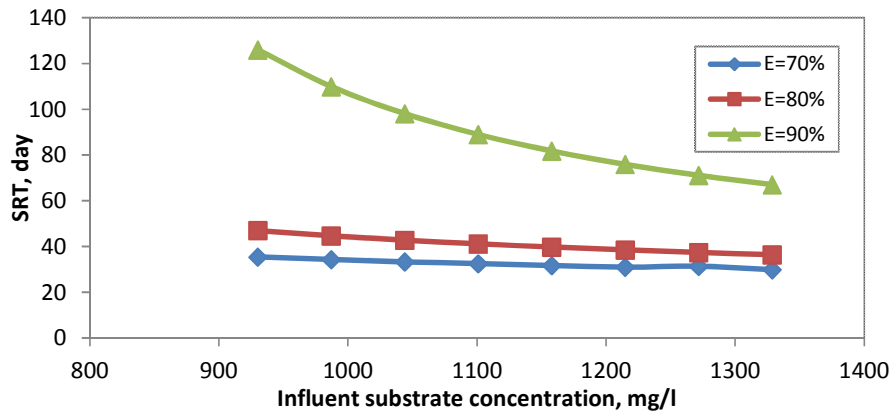

Fig. 11. Variation of SRT of anaerobic reactor with influent substrate concentration

4. CONCLUSION

The result indicated that there is a great decrease in the BOD level of the wastewater. This is because the micro-organisms start dying off as the food on which they depend decreased. The kinetic analysis was well described by the first order kinetic equation with a rate constant of 0.0319 day^{-1} showing that the rate of decomposition is a function of the concentration of the solid waste and other environmental factors. The kinetic parameters K_s, K_d and Y obtained indicated that the net sludge handling facilities would be large. A mathematical model was developed and used to predict the HRT and SRT of a continuous flow homogenous reactor under steady state based on the relationships of the substrate utilization rate and the biomass growth rate. The HRT increases linearly with increase in biomass concentration and increase in reactor efficiency. The SRT also showed a hyperbolic increase as influent substrate concentration decreased and as efficiency increased. The process design data obtained in this work can readily be employed in designing the anaerobic digestion system for a continuous reactor under steady state that can adequately treat restaurant wastewater effluent.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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