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Continuous process design model simulation for the anaerobic digestion of vegetable oil wastewater

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Abstract: Simulation of a mathematical model for the design of steady-state continuous reactors required for the anaerobic digestion of wastewaters was carried out. This was obtained so as to make the design of continuous stirred tank reactor (CSTR) that would be used for the anaerobic digestion of vegetable oil wastewater (VOW) possible. The model considered the kinetics of the process which has been previously determined during the batch digestion of the wastewater. The hydraulic retention time (HRT) and solid retention time (SRT) which are important parameters required for the design were estimated by varying different model parameters such as efficiency of reactor, influent substrate concentration (S_o) and biomass concentration (X) at various food-microorganism ratios (F/M). The HRT was calculated for different reactor efficiency (*E)* varying in the range of 70-95% at a constant influent substrate concentration. It was observed that the HRT increased with increase in efficiency ranging between 1.10 to 7.06 days. HRT also increased as the biomass concentration increased. SRT at constant influent substrate concentration and biomass concentration were observed to increase as the reactor efficiency increased. The effect of different substrate concentration on HRT to attain a targeted efficiency in the CSTR under steady state condition was also studied. It was observed that HRT linearly increased with increase in influent substrate concentration at constant reactor efficiency and biomass concentration. HRT also increased with decrease in biomass concentration and constant reactor efficiency for a particular substrate concentration. There was also an increase in HRT as reactor efficiency increased at constant biomass and influent substrate concentrations. SRT calculated at E1 (70%) and E2 (80%) efficiencies were observed to decrease with increase in influent substrate concentration. As the efficiencies of the reactor increased, SRT was also observed to increase. With the information obtained from the model simulation, a continuous stirred tank reactor that would treat VOW by anaerobic digestion could be designed.

Keywords: Anaerobic Digestion, Continuous Stirred Tank Reactor (CSTR), Process Design Model, Model Simulation, Vegetable Oil Wastewater (VOW)

1. Introduction

Nigeria has established industries like petroleum refinery, soap and detergent, breweries, textiles, food and beverage industries. The various effluents produced by these industries are discharged into the environment. Treatment of all kinds of wastewater before discharging into the environment is essential to prevent the pollution of water bodies where it is most likely to be discharged. These toxicans and pathogens when not sufficiently reduced cause a lot of diseases and premature deaths. Among the highly productive industries in Nigeria is the vegetable oil industry [1].

In order to obtain refined vegetable oil from seeds, many technological processes which include pre-treatment of oil seeds, manufacturing, refining and modification of oils are carried out. By-products and wastes are formed during these processes which when improperly disposed can cause pollution to the environment. These wastes include pesticides used in vegetable oil seed growing, chemical compounds like phenol, heavy metals from bleaching earth, catalysts used in the hydrogenation process, oxidizable substances and fats and oils [2].

There is growing interest in alternative renewable energy sources as the cost of available fuel rises [3]. The effect of the negative environmental impact caused by industrialization can be minimized and energy can be obtained as well by the means of anaerobic digestion. Anaerobic conversion of organic materials and pollutants is an established technology for environmental protection through the treatment of wastes and wastewater [4].The end product is biogas. This product is a useful renewable energy source as it is composed of a mixture of methane and carbon dioxide. Anaerobic digestion is a technologically simple process with a low energy requirement used to convert organic material from a wide range of wastewater types, solid wastes and biomass into methane [4]. It consists of the decomposition of organic material in the absence of free oxygen thereby producing biogas rich in methane, carbon dioxide, ammonia and traces of other gases including volatile fatty acids (VFA) within the reactor [5]. A much wider application of the technology is desirable in the current endeavors towards sustainable development and renewable energy production. Currently, the production of methane from wastes is receiving renewed attention as it can potentially reduce carbon dioxide (CO_2) emissions via the production of renewable energy and limit the emission of the greenhouse gas from especially animal manure [4]. The authors stated that this trend is supported by the growing market demand for 'green' energy and by the substantial optimization of anaerobic digestion technologies in the past decades, especially the development of modern 'high rate' and co-digestion systems. Anaerobic digestion when compared to other treatment methods have shown to be the principal method of an advanced technology for environment safeguards [6]. This is due to the fact that it handles the most important goals required in wastewater treatment which are lowering the amount of pollution generated and the reduction of dependency in fossil fuels through the production of bio-energy [5].

In choosing a reactor for wastewater treatment, certain factors are considered. Industries prefer technology that requires less capital, area and a higher reliability when compared to other options. The attractiveness of an anaerobic digestion system requires that it is able to run at high organic and hydraulic loading rates with a reduced operation and maintenance requirement [3]. The factors that affect these requirements include the amount of active biomass that can be retained by a reactor per unit volume, the contact opportunity between the retained biomass and the incoming wastewater; the diffusion of substrate within the biomass [3]; and optimum environmental conditions [5]. There are various types of reactors in use today and each design is related to the quality of the waste to be digested, with capital investment factors, and with the principal function of digestion. The different groups of reactors designs commonly used for the anaerobic digestion (AD) of wastes are batch, continuous one-stage and continuous two-stage reactors, tubular reactor, up-flow anaerobic sludge blanket (UASB), anaerobic sequencing batch reactor (ASBR), anaerobic filter (AF), and the plug flow reactor (PFR) [7]. These reactors and how they operate are also discussed in [7] and [8].

In a batch reactor, substrate is treated and discharged before the cycle is repeated [9]. The digester is filled once at the start of the process, with or without the addition of seed material, and allowed to go through all the degradation steps sequentially leading to the formation of biogas. A minimum amount of water is added and the leachate can be re-circulated to the top of the fermenting waste [10]. The liquid contents of the reactor are mixed completely during the process [9]. Anaerobic batch digestion is useful because it can be performed with simple, inexpensive equipment and with waste with total solids concentration as high as 90%, e.g, staw. It is also useful in laboratory scale studies in assessing the rate at which a material can be digested and in determining the yields of biogas obtainable. The batch reactor is a useful tool to improve the understanding of the outcome of anaerobic digestion processes [11] and is mainly used to blend chemicals or dilute concentrated chemicals [9]. The major disadvantages of batch systems are their large footprint, a possible need for a bulking agent and a lower biogas yield caused by impairment of the percolation process due to channeling or clogging due to compaction [10]. Another disadvantage of the system is that a separate influent tank and effluent tank are needed [4].

For plug flow reactors, fluid particles are passed through the reactors with little or no longitudinal mixing and leave in the same sequence in which they entered [9]. Plug flow reactor is found to be superior to the conventional processes due to low concentrations of VFA in the effluent, a high degree of sludge retention and stable reactor performance [3]. The disadvantage of this treatment process is in its restrictions due to the nature of wastewater to be treated, nature of reaction; whether homogeneous or heterogeneous, reaction kinetics for the treatment process, process performance requirements and the conditions of the environment where the treatment process would be carried out. Where the high rate hybrid filters provide high sludge retention times by means of sludge recycling which results in maximum efficiency at short hydraulic times, however, their performance with concentrated wastewater has been shown to be poor [9]. A common problem encountered in the industrial anaerobic plants is biomass washout which can be addressed by the use of membranes coupled with the anaerobic digester for biomass retention [3]. However, membrane separation has been considered for anaerobic reactors but the technology is still in a developmental stage [9].

In the continuous stirred tank reactor, it is assumed that complete mixing occurs instantaneously and uniformly throughout the reactor as fluid particles enter the reactor. Fluid particles leave the reactor in proportion to their statistical population. The time required to achieve complete mixing depends on power input and reactor geometry [9]. The content in the reactor is a mixture of fresh material and fully digested material. Examples of CSTR systems are sewage sludge digesters or well mixed anaerobic treatment pond. Some fresh water is fed into the digester on daily basis with an equal quantity of digested material being discharged. Degradation of the material is obtained when a sufficiently long hydraulic retention time (HRT) is observed [8].

According to [12], dairy wastewater has been treated using anaerobic digestion in CSTRs with the incorporation of a biofilm support in some of them. It was observed that 20%

better improvement in methane yield was obtained when compared to CSTRs operated without biofilm support systems. This showed that an improvement in the efficiency of digesters was obtained without biomass recycling. The authors also reported that anaerobic digestion of a mixture of pig manure, fish oil waste and waste from bentonite of edible oil filtration process for biogas has been carried out by the use of a laboratory scale CSTR operated at 30°C. During the experiment, an average methane content of 65% was obtained and after a HRT of 15 days, maximum methane production of 74% was obtained in the digester biogas. An investigation was carried out to obtain the continuous biogas production from fodder beet silage without manure addition using a CSTR. The content of methane in the biogas produced ranged between 62% and 64% [12]. The authors also reported an investigation on the effects of OLR, HRT and pH on conversion of food waste to hydrogen were investigated using a thermophilic CSTR. It was observed that after a 5 day HRT at a loading rate of 8g VS/L/d and a pH of 5.5, maximum operational conditions for continuous hydrogen production could be attained. Reference [6] studied the use of CSTR in the anaerobic digestion of petrochemical wastewater treatment by raising the organic loading rate. Results showed that highest COD elimination efficiency was 98%±0.5% at 7.5g COD/Ld OLR and 4d HRT, and the average methane produced was 65.49%. Anaerobic digestion of VOW in a CSTR is uncommon.

The anaerobic degradation of complex organic material involves sequence of subsequent steps which are carried out by different kinds of bacteria in a mixed population [13]. These steps or metabolic stages are explained in [5]. The performance of the bacteria in degrading the organic matter can be described by kinetics. Further, kinetics is an important tool to understand the anaerobic degradation, reactor design and operation. Its analysis is an accepted route for describing the performance of biological treatment systems and for predicting their performance. Generally, the results of kinetic studies obtained from experimental studies can be used for estimating treatment efficiencies of full scale reactors with the same operational conditions [13]. Simulation makes the design of full scale reactors easier without pre-experimentation on a pilot scale of the reactor to be designed. To ensure effective wastewater treatments in biological systems, Solids Retention Time (SRT) and Hydraulic Retention Time (HRT) need to be controlled.

Solids Retention Time (SRT) is the estimated time the activated-sludge solids are to be retained in the reactor. The growth rate of microorganism is controlled by SRT [14]. It plays a vital role in the removal of pollutants and in the reduction of quantity of unrestrained sludge. Microorganisms in the wastewater are not optimized for the current growth conditions when SRT is not controlled. One of the various methods used to make waste flow adjustments and control SRT include food-to-microorganism ratio (F/M) control also known as organic load [15]. This method requires TSS and BOD/COD estimations [14]. Hydraulic retention time (HRT) is the period in which a specific volume of liquid is retained in the working volume of a reactor. The inverse of HRT is F/M ratio [16]. The F/M ratio and the volume of the reactor determine the HRT of the wastewater treatment. The determination of required HRT will prevent unfavorable metabolic activities of the microbes and maintain a control of the biomass concentration [15, 16].

Simulation of a mathematical model in which HRT and SRT were estimated for the design of a continuous reactor for anaerobic digestion of wastes was developed by [17]. The model was developed to treat MSW in a continuous flow reactor unit under homogeneous steady state conditions. The simulation was carried out using the kinetic parameters obtained from [18] where the kinetics of batch anaerobic digestion of MSW was evaluated. The simulation model was applied in this work for the design of a CSTR for the anaerobic digestion of VOW using the kinetic parameters obtained by considering Monod's kinetics of biomass growth and substrate utilization in [19] while treating VOW in a batch anaerobic digester. CSTR has been applied to treat a lot of effluents but its use in the treatment of VOW is scarce in literature.

2. Materials and Methods

2.1. Batch Experimental Procedure

The batch digestion procedure was carried out as stated by [19]. During the batch digestion period, chemical oxygen demand (COD) and total suspended solids (TSS) were tested after every five-day interval from the point of charging to the end of the retention period. These parameters were analyzed in order to obtain some kinetic values which were evaluated from a simplistic design model applied by [18] and [20].

2.2. Kinetics of Batch Process Anaerobic Digestion

As described in [18] and [20], limited substrate consumption is a first order reaction which can be expressed as:

$$\frac{-dS}{dt} = KS \tag{1}$$

Where K = the rate constant
S = Substrate concentration
t = hydraulic retention time (HRT)

The above equation is characterized as exponential growth and the substrate concentration profile with respect to hydraulic retention time (HRT) as follows:

$$S_e = S_0 \exp(-Kt) \tag{2}$$

Where S_o is the influent substrate concentration (mg/l), S_e is the effluent substrate concentration (mg/l) and t is the hydraulic retention time (days).

Equation (2) shows the exponential growth of the organism as the substrate is utilized. Rearranging and taking natural logarithm of both sides of (2) gives (3) [13,18,20]:

$$\ln\left(\frac{S_e}{S_o}\right) = -Kt \tag{3}$$

Where K is the first order inactivation rate coefficient (l/day).

A linear plot of -ln (S_e/S_o) against t is obtained with the regression coefficient showing the order of reaction.

The rate of substrate utilization (U) is related to effluent substrate concentration (S_e) in (4) according to [18,20].

$$\frac{1}{U} = \frac{K_S}{K}\frac{1}{S} + \frac{1}{K} \tag{4}$$

From (4), a linear plot of *1/U* against *1/S$_e$* gave *1/U* as intercept and K_s/K as slope from where *K* and K_s were obtained.

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

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

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

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

K is used to determine the volume of biological reactors. The greater the value of '*K'*, smaller will be the size of the reactor [21]. *K* also shows whether inoculation is required for better performance [18,20]. This makes the design of bioreactors easier. K_s give an idea about the change in the specific growth rate of bacteria with a change in the concentration of the growth limiting substrate [21]. The specific rate of substrate utilization is related to mean cell residence time [18,20] in (5)

$$\frac{1}{\theta} = YU - K_d \tag{5}$$

Where $\theta = \frac{X}{dX/dt}$ = the mean cell residence time (day) = SRT = sludge age

U = the specific rate of substrate utilization

Y = the biomass yield/microbial growth yield (mg/mg)

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

From (5), biomass yield (Y) and endogenous decay coefficient (K_d) were obtained from the plot of $1/\theta$ versus *U*. *Y* is used to estimate the total amount of sludge produced as a result of wastewater treatment. K_d is used to determine the net amount of sludge to be handled. Hence the size and cost of the sludge handling facilities can be determined from this information since the higher the value of *Y* and K_d, the smaller the sludge production and sludge handling facilities [21].

The maximum specific growth rate of microorganism, μ_{max} is evaluated from (6).

$$K = \frac{\mu_{max}}{Y} \tag{6}$$

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

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

Also from [22] and the Monod equation,

$$\mu_{net} = \mu_{max}\frac{S}{K_s + s}[X] - K_d[X] \tag{7}$$

Dividing through by X ,

$$\mu_{net} = \mu_{max}\frac{S}{K_s + s} - K_d \tag{8}$$

μ_{net} = net specific growth rate of microorganisms (day^{-1})

2.3. Continuous Process Design Model for Anaerobic Digestion

Reference [17] proposed a kinetic model considering the case of continuous mode homogeneous reactor under steady state condition.

The HRT at any desired efficiency, E (in fraction) of the reactor and food to microorganism can be evaluated from eq. (9) can be expressed as

$$t = \frac{ES_O[K_S + S_O(1-E)]}{KXS_O(1-E)} \tag{9}$$

where $X = F/M$ (from M = 0.7 – 1.0) = S_o/M

F/M = food to microorganism ratio

As soon as the hydraulic retention time is evaluated, the volume of the reactor can be determined as follows

$$V = Qt \tag{10}$$

Where V = volume of the reactor (m^3)

Q = the desired flow rate (m^3/day)

The solid retention time, SRT (days) required for the anaerobic digestion system, can be determined as

$$\theta = \frac{X}{r_g - K_d X} = \frac{X}{-\frac{YdS}{dt} - K_d X} \tag{11}$$

Where r_g = volumetric cell production rate (gVSSm^{-3}day^{-1})

X = F/M ratio

Again, according to [17] and [23], the continuous reactor under steady state condition, (11) can be modified as

$$\theta = \frac{X}{Y\frac{S_0 - S}{t}K_d X} = \frac{X}{-Y\frac{ES_0}{t} - K_d X} \tag{12}$$

Table 1. *Kinetic parameters used for the study*

Parameters	Values
K	0.8215day^{-1}
K_s	163.31mg/l
K_d	0.0838day^{-1}
Y	0.2813mg/mg

The retention period (hydraulic retention time, HRT, days and solid retention time, SRT, days) for the continuous reactor is determined after K_s, K, S_e and S_o have been evaluated from batch experiment. The kinetic parameters obtained from [19] after the batch digestion of VOW is shown in Table 1.

2.4. Simulation Methodology

The important CSTR process design parameters for the anaerobic digestion of VOW are influent and effluent substrate concentration, biomass concentration, hydraulic retention time (HRT), solid retention time (SRT) and the kinetic constants [17]. The HRT and SRT are obtained from (9) and (12). Since the vegetable oil wastewater being considered for treatment is that analyzed by [19] from batch digestion of VOW, hence the kinetic parameters, the substrate concentrations and biomass concentration are already known.

In the present study, the biodegradable organics were represented as influent COD (640mg/l) which was initially analyzed by [19]. Hence, the values of HRT and SRT which are required in the design of a CSTR for the anaerobic digestion of VOW can be obtained.

3. Results and Discussion

For the design of a steady state continuous stirred tank reactor (CSTR) that would be used to treat VOW wastewater by anaerobic digestion, the hydraulic retention time (HRT) at which the reactor would operate is required. The model simulation was evaluated for different reactor efficiencies (*E*) of 70, 75, 80, 85, 90 and 95% with F/M ratios of 0.7, 0.75, 0.8, 0.85, 0.9, 0.95 and 1.0 respectively. These were considered at a constant influent COD of 640mg/l. The biomass concentrations calculated for F/M ratios between 0.7-1.0 were determined to be 914.3, 853.3, 800, 753, 711.7, 673.7 and 640mg/l respectively. It was observed that the biomass concentration decreased as the F/M ratio increased, although the rate at which the biomass concentration decreased was not proportional. The biomass concentration decreased by 61, 53.3, 47, 41.9, 37.8, 33.3, mg/l as the F/M ratio increased from 0.7-1.0 respectively. This showed that the rate at which the biomass concentration decreased became higher as microorganisms increased. The variation of HRT for the various efficiencies of anaerobic digestion of VOW is shown graphically in Fig. 1 and the values are given in Table 2. It was observed that the HRT increased with increase in the efficiency of the reactor. This was observed to have a hyperbolic curve. Also, HRT increased with increase in F/M ratio. For the reactor to operate at 95% efficiency, HRT of 7 days at F/M ratio of 1.0 is required. This is lesser than the time applied in the batch treatment of VOW [19]. Hence treatment using CSTR is less time consuming therefore less expensive.

The SRT required for the anaerobic digestion of VOW in a CSTR under steady state was calculated for different removal efficiencies (*E)* of COD varying in the range of 70, 75, 80, 85, 90 % at a constant influent COD of 640mg/l and F/M ratio of 0.7. The biomass concentration was not varied while varying efficiency at a fixed influent COD for the determination of SRT as there was no effect in the values obtained [17]. The calculated values of SRTs at different treatment efficiencies are represented graphically in Fig. 2 and the values are given in Table 2. The SRT was observed to increase as the digestion efficiency increased.

The HRT required for targeted treatment efficiency at various substrate concentrations of the wastewater under steady state condition was determined. The influent substrate concentration was varied between 530.28-914.3 mg/l. The biomass concentration was taken as 914.3 and 640 mg/l corresponding to F/M ratio of 0.8 and 1.0 respectively. The HRT was calculated for 70, 80 and 90% reactor efficiencies in response to F/M ratio of 0.8 and 1.0. It was observed that the HRT required for anaerobic digestion of the wastewater increased with increase in influent substrate concentration at steady reactor efficiency and biomass concentration. HRT also increased as biomass concentration decreased for particular reactor efficiency. Again, at a constant biomass concentration, the HRT would increase if the reactor efficiency is increased. The variation of HRT as influent substrate concentration increased has been shown in Fig. 3 and the values are provided in Table 3.

The effect of different substrate concentration on SRT value to attain a targeted efficiency under steady state condition was also studied on VOW digestion. The influent concentration was varied in the range of 530.28-914.3 mg/l. The biomass concentration was taken as 914.3 and 640 mg/l corresponding to F/M ratio of 0.8 and 1.0. The SRT was calculated for 70 and 80% reactor efficiency in response to F/M ratio of 0.8 and 1.0 respectively. The variation of SRT at different reactor efficiencies as influent substrate concentration increased is shown in Fig. 4and Table 3. It was observed that SRT decreased with increase in influent substrate concentration. Increasing the reactor efficiency at a constant substrate concentration however brought about an increase in SRT. The profile of SRT also indicated a hyperbolic nature and does not dependent on the biomass concentration [17].

Table 2. *Variation of HRT and SRT with variation of efficiency of anaerobic digestion of vegetable oil wastewater*

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	640	914.3	853.3	800	753	711.1	673.7	640	1.10	1.18	1.26	1.34	1.42	1.50	1.58	10.53
75	640	914.3	853.3	800	753	711.1	673.7	640	1.29	1.38	1.48	1.57	1.66	1.75	1.84	11.67
80	640	914.3	853.3	800	753	711.1	673.7	640	1.55	1.66	1.77	1.88	1.99	2.11	2.22	13.39
85	640	914.3	853.3	800	753	711.1	673.7	640	1.96	2.10	2.24	2.38	2.52	2.66	2.79	16.45
90	640	914.3	853.3	800	753	711.1	673.7	640	2.72	2.91	3.11	3.31	3.50	3.70	3.89	23.01
95	640	914.3	853.3	800	753	711.1	673.7	640	4.94	5.29	5.65	6.00	6.35	6.71	7.06	49.74

Table 3. *Variation of HRT and SRT with variation of influent substrate concentration of anaerobic digestion of VOW*

Influent COD, S_o	Reactor Efficiency (%)			Biomass Concentration, X (mg/l)		HRT (day)						SRT (day)	
(mg/l)	E1	E2	E3	F/M=0.8X1	F/M=1.0X2	E1 +X1	E1 + X2	E2 + X1	E2 + X2	E3 + X1	E3 + X2	E1	E2
530.28	70	80	90	914.3	640	1.00	1.43	1.44	2.05	2.59	3.70	17.84	23.71
585.14	70	80	90	914.3	640	1.05	1.50	1.49	2.13	2.66	3.80	16.78	21.95
640.0	70	80	90	914.3	640	1.10	1.58	1.55	2.22	2.72	3.89	16.04	20.65
694.86	70	80	90	914.3	640	1.15	1.65	1.61	2.30	2.79	3.99	15.31	19.48
749.72	70	80	90	914.3	640	1.21	1.72	1.67	2.38	2.86	4.08	14.70	18.50
804.58	70	80	90	914.3	640	1.26	1.80	1.73	2.47	2.92	4.17	14.27	17.76
859.44	70	80	90	914.3	640	1.31	1.87	1.95	2.55	2.99	4.27	13.81	17.04
914.3	70	80	90	914.3	640	1.36	1.94	1.84	2.63	3.05	4.36	13.41	16.41

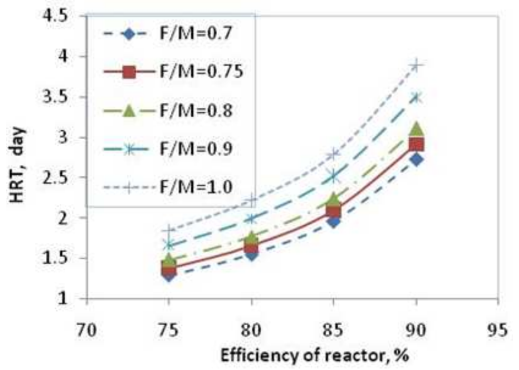

Fig 1. *Variation of HRT with efficiency of anaerobic digestion of VOW*

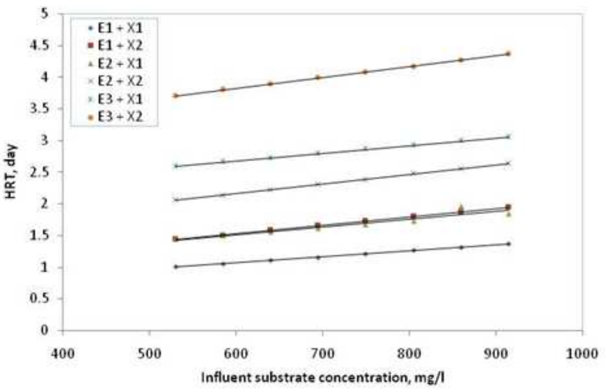

Fig 2. *Variation of SRT with efficiency of anaerobic digestion of VOW*

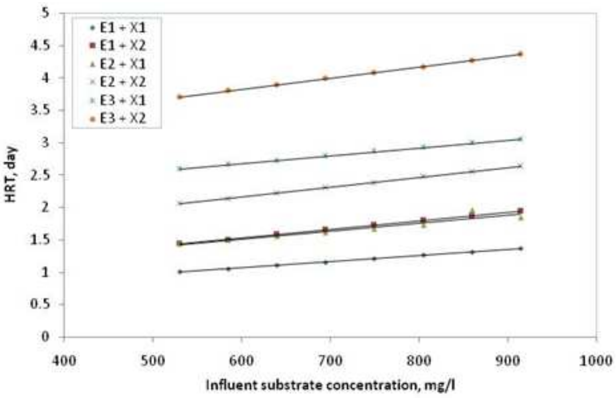

Fig 3. *Variation of HRT of anaerobic reactor for VOW digestion with influent substrate concentration (E1=70%, E2=80%, E3=90%, XI=914.3mg/l, X2=640mg/l)*

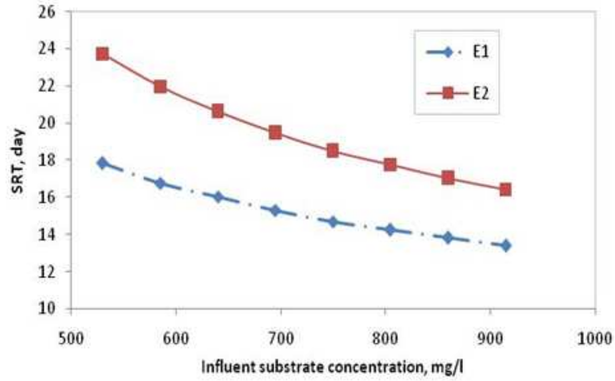

Fig 4. *Variation of SRT of anaerobic reactor for VOW digestion with influent substrate concentration*

4. Conclusion

The kinetic parameters obtained from the batch process anaerobic digestion of VOW were used to simulate a model for the design of continuous reactors for the same treatment method and wastewater. This was done by obtaining the HRT and SRT that would be required for the treatment at any given reactor efficiency. With these data, the volume and flow rate of the reactor can be calculated. While varying the HRT and SRT with variation of efficiency, the reactor operation had an upward shift as the efficiency increased from 70-95%. Variation of HRT and SRT with influent substrate concentration for continuous process indicated that the HRT increased with increase in varying substrate concentration. The SRT on the other hand decreased as influent substrate concentration increased in a hyperbolic pattern. It could be concluded that a simplistic process design model for anaerobic digestion of VOW is possible to be developed. The developed mathematical model can be employed to predict the process control parameters like the HRT and SRT of both batch and continuous flow type homogenous reactors under steady state condition.

Nomenclature

AD	Anaerobic Digestion
AF	Anaerobic Filter
ASBR	Anaerobic Sequencing Batch Reactor
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
COD/Ld	Chemical Oxygen Demand per litre per day
CO_2	Carbon dioxide

CSTR	Continuous Stirred Tank Reactor
E	Efficiency (in fraction) of the reactor
F/M	Food to Microorganism ratio
HRT	Hydraulic Retention Time (day)
K	First Order Inactivation Rate Coefficient (l/day)
K	Maximum Rate of Substrate Utilization (day^{-1})
K_d	Endogenous Decay Coefficient (day^{-1})
K_s	Half-velocity constant, mg/l
MSW	Municipal Solid Waste
OLR	Organic Loading Rate
PFR	Plug Flow Reactor
Q	Flowrate of the Reactor (m^3/day),
r_g	Volumetric cell production rate ($gVSSm^{-3}day^{-1}$)
S_0	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)
SRT	Solid Retention Time (day)
t	Time for batch digestion, day
t	Hydraulic Retention Time (day) for continuous reactor
t_c	Solid Retention Time (day) for the continuous reactor
TSS	Total Suspended Solid
$U = \frac{ds/dt}{x}$	Rate of Substrate Utilization (mg COD/L/day)
V	Volume of the Reactor (m^3)
VFA	Volatile Fatty Acids
VOW	Vegetable Oil Wastewater
VS/L/d	Volatile Solids per litre day
WHO	World Health Organization
X	Average Total Suspended Solid (biomass concentration) (mg/l)
Y	Biomass yield (mg/mg)
$\theta = \frac{x}{dx/dt}$	Mean cell residence time (day)
$\mu_{\max}$	Maximum Specific Growth Rate of Microorganisms (day^{-1})
μ_{net}	Net Specific Growth Rate of Microorganisms (day^{-1})

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