

# Kinetic Modeling of Continuous Stirred Tank Reactor - Operating On Distillery Effluent

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## Research

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# Abstract

To identify the viability and performance, distillery effluent having very high organic content was studied on continuous stirred tank reactor (CSTR). Under different organic loading rates (OLR), optimum conditions for highest chemical oxygen demand (COD) removal and biogas generation was found to be for OLR of 0.10 COD kg /d to 0.11 COD kg /d. Highest COD exertion efficiency was found to be around 73% for OLR of 9.166 kg COD/m<sup>3</sup>/d when hydraulic retention time (HRT) reduced from 15 to 14 days. Biogas generation was observed to be around 30 L/d with a conversion coefficient of 0.405 and 0.12 volatile fatty acids (VFA) to alkalinity ratio were recorded in this stage. Applying the modified Stover Kincannon model to the reactor, the maximum removal rate constant ( $U_{max}$ ) and saturation value constant ( $K_b$ ) were found to be 17.123 kg/m<sup>3</sup>/day, and 33.471 kg/m<sup>3</sup>/day respectively. These records are predominantly significant, when operating the anaerobic biodigesters for treating the distillery effluent along with the production of biogas as an energy sources. CSTR can effectively be employed in treatment of this effluent however post bio-digestion effluent still contains considerable COD. To meet the pollution norms and standards it needs to be treated further. To understand the complex biological treatment process of this effluent further trials are required to be conducted.

## Introduction

The distillery produces alcohol using molasses which is a byproduct of the sugar manufacturing process. Fermentation and Distillation processes are required to produce alcohol. The distillery effluent is known as a spent wash and is having dark brown in color. Spent wash produced after distillation process in distillery. The generation of effluent from the distillery is about 12–15 times the production of alcohol (1). The spent wash has very high values of biochemical oxygen demand (BOD) (around 45000 mg/L) and chemical oxygen demand (COD) (around 110000 mg/L) (2). The spent wash is highly acidic (around pH 4.0) with high suspended solids (TSS) (2.0–2.5 kg/m<sup>3</sup>) (3). The spent wash is toxic to the surrounding environment (4). The spent wash also contains nutrients like nitrogen, phosphorus, and potassium (5).

As per the Ministry of Environment and Forests, Govt. of India (MoEF), the distillery industry recognized as one of the heavily polluting industries (6). There are around 400 distilleries operating at present in states of the India. The average generation of the spent wash is up to 15 liter per liter of the alcohol produced, depending on type of process and quality of molasses used, etc. (7).

In the distillery industry, only around 12% of raw material is converted into the product and rest is converted in to waste. There are various technologies available for the treatment of the spent wash. These technologies include mainly resource recovery from spent wash and disposal. The secondary and tertiary treatments are not technically and economically feasible for mitigating the problems associated with the treatment and disposal of spent wash (8). Because of the high BOD and COD values, the spent wash is having great potential to produce biogas through anaerobic digestion. From the available technologies, anaerobic digestion of the spent wash for energy recovery is reported to be the most

effective method (9). Anaerobic treatment of the spent wash with biogas recovery is being adopted nowadays by many alcohol industries in India (10).

Various types of anaerobic biodigesters have been tried at both pilot scales as well as in full- scale operations (11). The anaerobic bio-digestion of the spent wash is particularly suitable because their COD/N/P ratio is unbalanced for aerobic treatments that need phosphorus and nitrogen addition (12). Along the banks of Krishna River in South Maharashtra and North Karnataka states of India, on very large area sugarcane is being cultivated as it is considered as a cash crop. In this region, many sugars and the distillery industries are operating and producing enormous quantity of spent wash (13).

The main purpose of the present study was to assess the influence of organic loading rate on the treatment efficiency of a continuous stirred tank reactor (CSTR) relating the process parameters, COD, and the biogas production. The results of this study may be useful in investigating the performance and overall feasibility of CSTR for the treatment of spent wash. The various factors affect the performance of the digestion process. The activity of microorganisms, substrate utilization and biogas formation are the key factors in anaerobic digestion. The important process parameters required to be considered includes Alkalinity, VFA, COD exertion, and TSS (14).

## Material And Method

### Substrate:

For the present study spent wash and seed culture was provided by Lokmangal Sugar and the distillery Industry located at Solapur, Maharashtra, India. Table 1 shows the characteristics of the spent wash.

Table 1  
Key characteristics of distillery effluent

Parameters	Values of Raw spent wash
pH	3.0–4.5
BOD <sub>5</sub>	55000–65000 mg/L
COD	110000–140000 mg/L
Total Solids (TS)	90000–140000 mg/L
Total volatile solid (TVS)	80000–100000 mg/L
Total Suspended Solids (TSS)	11000–14000 mg/L
Total Dissolved Solids (TDS)	80000–130000 mg/L
Chlorides	7000–8000 mg/L
Phosphate	2300–3000 mg/L
Total Nitrogen	6000–8000 mg/L

## Start-up of the CSTR:

In the present investigation, a plastic tank was used as a reactor shown in Fig. 1. The reactor has provision for inlet, outlet, and overflow of effluent. The outlet of biogas was connected to the tin lamp which was partially filled with water to burn the biogas produced after passing through water. Mechanical stirrer with a motor was mounted at top of the bottle. The entire setup was checked for liquid as well as gas leakage if any. Activated seed culture from full-scale functioning digester was used as a seed material. The seed was diluted to dilution factor 3 to initiate the process. The important parameters of seed culture were as shown in Table 2. Continuous feeding of spent wash to the reactor was started at a low rate of 0.01 kg COD per day with continuous stirring of reactor liquid. Feeding was continued till the stabilization of digester parameters was observed. An increase in COD loading was done only after achieving steady-state conditions. The parameters of the CSTR effluent was monitored and analyzed after regularly intervals. After every stable condition, feeding was increased with 0.01 kg COD. The stable steady-state condition refers to very little or no variation in COD of overflow effluent, Alkalinity, or VFA of reactor effluent sample (15). Stable VFA to alkalinity ratio also considered as a steady-state condition. It can also be examined by stable gas production (16). The analysis was conducted after 24 hrs of change in OLR. As the feeding quantity was low as compared with the volume of CSTR, the pH of the influent was not adjusted before feeding. Gas generation was observed by flame height. Samples of the CSTR were analyzed for pH, Temperature, Suspended Solids (SS), Total Dissolved Solids (TDS), Volatile Fatty Acids (VFA), Alkalinity, COD etc. The pH was tried to maintain within the optimum range of 6.5 to 7.5 to enhance the growth and activity of anaerobic bacteria throughout the study. The performance of the CSTR for different organic loading rates (OLRs) was evaluated in terms of COD removal efficiency and

Table 2  
Characteristics of activated  
seed

Parameter	Value
pH	7.8
Temperature	35 °C.
VFA	1300 mg/L
Alkalinity	31000 mg/L
TDS	57000 mg/L
TSS	34000 mg/L
COD	36000 mg/L

## Results And Discussions

Characteristics of raw spent wash (RSW), Reactor effluent, and overflow effluent were analyzed as per the standard methods for the examination of Water and Wastewater (17). The COD and BOD values were observed to be 126000 mg/L and 57000 mg/L respectively resulting in COD to BOD ratio 2.2 which indicated the spent wash is highly suitable for biological digestion.

### Organic and Hydraulic loading rates:

The organic loading rates from 0.01 kg COD per day to 0.16 kg COD per day was applied with an increment of 0.01 kg COD. Hydraulic Loading Rate (HLR) (L/d) was adjusted as per the required organic loading rate (OLR) (kg/d). The hydraulic loading rate and corresponding hydraulic retention time (HRT) (Days) for the CSTR model were shown in Table 3.

Table 3  
Influent COD and OLR details.

Influent COD (kg/L)	Hydraulic Loading Rate (L/d)	Organic Loading Rate COD (kg/d)	Hydraulic Retention Time (d)
0.122	0.08	0.01	146.4
0.122	0.16	0.02	73.2
0.122	0.25	0.03	48.8
0.122	0.33	0.04	36.6
0.130	0.38	0.05	31.2
0.130	0.46	0.06	26.0
0.130	0.54	0.07	22.3
0.130	0.62	0.08	19.5
0.130	0.69	0.09	17.3
0.128	0.78	0.1	15.4
0.128	0.86	0.11	14.0
0.128	0.94	0.12	12.8
0.128	1.02	0.13	11.8
0.119	1.18	0.14	10.2
0.119	1.26	0.15	9.5
0.119	1.34	0.16	8.9

## Effect of OLRs on CSTR parameters:

The results are reported in Fig. 2–6, which summarizes the performance of CSTR at steady-state conditions. Methanogenesis is sensitive to both high and low pH and occurs between pH 6.5 and pH 8 hence reactor pH maintained between this ranges. From the commencement of the process, the temperature of the reactor was observed as the stability and efficiency of the anaerobic treatment process are greatly influenced by temperature (18)(19). Reaction rate, the dominance of certain biochemical pathways, and microbial activity are some of the areas known to be affected by temperature (20). Hence, paying attention to the reactor temperature is essential, since small temperature variation can considerably influence the reactor performance and the biogas (21).

The growth and decay rates are different at different temperatures hence; Mixed Liquor Suspended Solids (MLSS) concentration was correlated to temperature variations (Fig. 2.). The steady growth of solids was observed for constant reactor temperatures whereas higher growth was recorded during rise in reactor

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temperature. Highest COD removal efficiency of 72% was recorded at temperature  $37 \pm 1$  °C when MLSS was around 36000–44000 mg/L. This performance is slightly at the lower side as comprised with membrane anaerobic bioreactor which results in 76% COD removal efficiency at 37 °C (18). Figure 2 summarizes the variation of the MLSS and Temperature. Reactor temperature increased up to 37 °C. Further, a decrease in HRT, results in reduction in COD removal efficiency, this could be a combined effect of high substrate availability and low net biomass growth rate. Further studies on CSTR needs to be conducted to reduce the COD of overflow effluent. The drop in temperature was predicted after further increase in HLRs.

For variable organic loading rates (OLR), the performance of reactor was examined in terms of biogas generation and % COD reduction. The optimum organic loading for highest COD removal from the spent wash has been examined and shown in Fig. 3. It was observed that COD removal reached a maximum of 73% when OLR is 0.11 kg COD per day with 9.17 kg COD/ m<sup>3</sup>/ d. Some studies have reported optimum conditions for COD exertion of the spent wash to be between OLR of 8 and 10 kg COD / m<sup>3</sup>/ d and on further increasing the OLR, hydraulic shock loading conditions would result with the rapid drop in COD reduction activity in case of Up-flow Anaerobic Sludge Blanket Reactor (UASBR) with fixed film (22). CSTR performance was on the slightly lower side in terms of the COD reduction under a similar range of OLRs. This may be because of a better reaction rate shown by fixed film reactors. At higher OLRs, it was observed and predicted that there is a gradual drop in COD reduction, unlike the fixed-film reactors which shows a sharp drop in COD removal efficiency. An increasing volume of biogas was observed during the treatment process which indicated the presence of a growing number of methanogenic bacteria. Characterization of seed present in the digester at different stages of bio-digestion is required to be done to better understand the role of microorganisms in performance of CSTR.

Generally, the volume of biogas can be calculated as; Volume of biogas =  $\alpha Q (S_{in} - S_{out})$ . Where Q the feed-flow rate in m<sup>3</sup>/d,  $S_{in}$ , and  $S_{out}$  are the influent and effluent substrate concentration (kg/ m<sup>3</sup>) and  $\alpha$  is the conversion coefficient of the substrate in biogas. For biogas produced by the degradation of COD as substrate a conversion coefficient  $\alpha = 0.45$  applies (23). In our study, from the recorded biogas quantities from full-scale CSTR, the conversion coefficient was calculated and it was found to be 0.405 and the same is used to calculate the biogas generation to get relevant results. It was observed that optimum biogas produced was in the range of 29 L to 32 L. The anaerobic process is very sensitive to temperature as mentioned earlier; it was observed that temperature increases from 32 °C to 37 °C from the commencement of process study to produce maximum COD exertion of 73% for HRT of 14 days.

During the present study, COD variations observed between 120000 mg/l to 130000 mg/l. Figure 4 shows variation in HRT with OLRs and the corresponding removal of COD. It was observed that the highest COD exertion occurs when OLR increased from 0.10 kg/d to 0.11 kg/d this causes reduction in HRT from 15 d to 14 d. these observations are similar to the study reported by Benabdallah El-Hadj (2007) (24). Further, it is observed that the decrease in HRT from 14 d to 8 d, COD removal decreased from 72.6% to 68%.

Reactor shows VFA to alkalinity ratio at this stage as 0.34.

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Volatile Fatty Acids and Alkalinity of reactor samples were observed and are shown in Fig. 5. The effluent alkalinity is higher than the influent alkalinity. This indicates that adequate buffering capacity was present in the reactor due to which reduction in pH was not observed even after an increase in the concentration of VFA in the reactor, particularly at high OLRs (above 0.10 kg/d). This indicates that the efficiency of the reactor decreased due to sulfide inhibition rather than VFA inhibition. The increase in VFA concentration in the reactor represents the incomplete conversion of VFA into the final end product (CH<sub>4</sub>) may be due to the reduction in retention time or due to sulfide toxicity to the methanogenic bacteria. Similar results were reported by Gupta and Singh with an anaerobic hybrid reactor. This indicates biogas production is strongly correlated with the OLR (25). The impact of VFA accumulation was reflected in the decrease in COD removal.

VFA has been identified as one of the very important characteristics during anaerobic digestion and is considered a vital parameter for anaerobic treatment (26). The study shows that methanogenesis appears to be an alkalizing process, as it consumes hydrogen and H<sub>3</sub>O<sup>-</sup> ions (27). Figure 6 shows the variation of pH and VFA to alkalinity ratio for all ranges of OLRs. It is extremely difficult to maintain the pH of the reactor constant. VFA production was found to be increasing with an increase in organic loading due to the high metabolic activity of acid-forming bacteria and the Alkalinity of digester is considerably affected by the organic loading rate. The decrease in alkalinity with an increase in OLR can be attributed to an increase in VFA concentration in the reactor effluent. Further, better results could be achieved by increasing the buffering capacity of the reactor.

## Kinetic Modeling

The kinetic model proposed by Stover Kincannon relates the organic substance utilization rate as a function of OLR at steady-state conditions Eq. (1).

$$\frac{dS}{dt} = \frac{Q(S_i - S_e)}{V} \quad (1)$$

The original Stover Kincannon model is described as in Eq. (2).

$$\frac{dS}{dt} = \frac{Q(S_i - S_e)}{V} = \frac{U_{max}(\frac{QS_i}{V})}{K_b + (\frac{QS_i}{V})} \quad (2)$$

Rearrangement of Eq. (2) gives the relationship

$$\left(\frac{dS}{dt}\right)^{-1} = \frac{V}{Q(S_i - S_e)} = \frac{K_b V}{U_{max} Q S_i} + \frac{1}{U_{max}} \quad (3)$$

The model applied to the reactors data where S is digester substrate concentration (kg COD /m<sup>3</sup> in the Eq. (3)), dS/dt is substrate removal rate (kg/m<sup>3</sup> per d), U<sub>max</sub> is maximum removal rate constant (kg/m<sup>3</sup>

per d),  $K_b$  is saturation value constant ( $\text{kg}/\text{m}^3$  per d)

If  $(dS/dt)^{-1}$  is considered as  $V/Q (S_i - S_e)$ , which is the inverse of the loading removal rate, and this is represented and plotted with the inverse of the total loading rate  $V/ (QS_i)$ , it will produce a straight line. The intercept of these lines is  $1/U_{\max}$ , and the slope of the lines is  $K_b/U_{\max}$ , respectively. Figure 7, shows the results on the graphs. The graph represents  $Q (S_i - S_e)/V$  versus  $QS_i/V$  for all the HRT considered for the study. Table 4 shows, Stover and Kincannon model table showing values for X-axis and Y-axis for the CSTR lab model. The maximum removal rate constant  $U_{\max}$  ( $\text{kg}/\text{m}^3/\text{d}$ ) and is a saturation value constant  $K_b$  ( $\text{kg}/\text{m}^3/\text{d}$ ) was determined as below

$$\text{Intercept} = 0.0584$$

$$U_{\max} = \frac{1}{\text{Intercept}} = 0.0584 \text{ kg}/\text{m}^3/\text{d}$$

$$\text{Slope} = 1.9547$$

$$K_b = \text{Slope} * U_{\max} = 33.471 \text{ kg}/\text{m}^3/\text{d}$$

Table 4  
Stover and Kincannon model table showing values for X-axis and Y-axis for CSTR lab model

V (m <sup>3</sup> )	S <sub>i</sub> (kg COD/m <sup>3</sup> )	S <sub>e</sub> (kg COD/m <sup>3</sup> )	Q (m <sup>3</sup> /d)	V/(QSi) (m <sup>3</sup> d/kg)	V/Q (Si-Se) (m <sup>3</sup> d/kg)
0.012	122	58	0.00008	1.230	2.344
0.012	122	57	0.00016	0.615	1.154
0.012	122	55	0.00025	0.393	0.716
0.012	122	53	0.00033	0.298	0.527
0.012	130	52	0.00038	0.243	0.405
0.012	130	49	0.00046	0.201	0.322
0.012	130	45	0.00054	0.171	0.261
0.012	130	40	0.00062	0.149	0.215
0.012	130	39	0.00069	0.134	0.191
0.012	128	35	0.00078	0.120	0.165
0.012	128	35	0.00086	0.109	0.150
0.012	128	37	0.00094	0.100	0.140
0.012	128	36	0.00102	0.092	0.128
0.012	119	36	0.00118	0.085	0.123
0.012	119	37	0.00126	0.080	0.116
0.012	119	38	0.00134	0.075	0.111

The important characteristic of the plot is the steady loss in efficiency with raised organic loads. The kinetic constants  $K_b$  and  $U_{max}$  can be calculated as 33.471 kg/m<sup>3</sup>/d and 17.123 kg/m<sup>3</sup>/d from Fig. 7. The regression line had an  $R^2$  of 0.9995, verifying the accuracy of Eq. (2).

The obtained values of  $U_{max}$  and  $K_b$  can be used to find the reactor volume to reduce the organic matter from  $S_i$  to  $S_e$ . It is also used to find  $S_e$  (effluent concentration) for known or given  $V$  and  $S_i$ .

Mass balance for an anaerobic reactor can be written as

$$\{\text{Mass in X volume of media}\} = \{\text{Mass out X volume of media}\} + \{\text{Mass biodegraded}\}$$

$$QS_i = QS_e + V \left( \frac{dS}{dt} \right)$$

4

Further, in the above relationship (4),  $dS/dt$  can be replaced as below.

$$QS_i = QS_e + V \left( \frac{U_{max} \left( \frac{QS_i}{V} \right)}{K_b + \left( \frac{QS_i}{V} \right)} \right)$$

5

The above equation can be further simplified for the calculation of volume required for anaerobic reactor or concentration of effluent.

$$V = \frac{QS_i}{\left( \frac{U_{max} S_i}{S_i - S_e} \right) - K_b}$$

6

$$S_e = S_i - \frac{U_{max} S_i}{K_b + \left( \frac{QS_i}{V} \right)}$$

7

Above Eq. (7) can be used to compute concentration in effluent from known influent concentration and OLR for the CSTR. Table 5 shows the equivalent effluent concentrations predicted using the above equation and observed values during the study, which verifies the applicability of the model.

**Table 5: Observed and predicted values of effluent organic concentration ( $S_e$ ) for CSTR lab model**

Q (m <sup>3</sup> /d)	S <sub>i</sub> (kgCOD/m <sup>3</sup> )	Observed S <sub>e</sub> (kgCOD/m <sup>3</sup> )	U <sub>max</sub> (kg/m <sup>3</sup> /d)	K <sub>b</sub> (kg/m <sup>3</sup> /d)	Predicted $S_e = S_i - \frac{U_{max}S_i}{K_b + \left(\frac{QS_i}{V}\right)}$
0.00008	122	58	17.123	33.471	58.00
0.00016	122	57	17.123	33.471	57.06
0.00025	122	55	17.123	33.471	54.98
0.00033	122	53	17.123	33.471	52.99
0.00038	130	52	17.123	33.471	51.81
0.00046	130	49	17.123	33.471	48.97
0.00054	130	45	17.123	33.471	44.94
0.00062	130	40	17.123	33.471	40.14
0.00069	130	39	17.123	33.471	39.03
0.00078	128	35	17.123	33.471	34.62
0.00086	128	35	17.123	33.471	34.62
0.00094	128	37	17.123	33.471	36.94
0.00102	128	36	17.123	33.471	36.18
0.00118	119	36	17.123	33.471	36.07
0.00126	119	37	17.123	33.471	37.07
0.00134	119	38	17.123	33.471	38.05

Similar modeling was done by Bhavik K. Acharya in his Kinetic modeling, and microbial community assessment study of anaerobic biphasic fixed-film bioreactor treating the distillery spent wash (28). High strength distillery spent wash was treated through biphasic continuous mode, up-flow fixed film reactor having a volume of 3L. In this study, the anaerobic digestion process, microorganisms' community structure, and process kinetics were studied. Also, by using the Stover Kincannon model to the digester, the maximum removal rate constant (U<sub>max</sub>) and saturation value constant (K<sub>b</sub>) was found and observed to be 2 kg/m<sup>3</sup>/d and 1.69 kg/m<sup>3</sup>/d respectively.

The observations, results, and calculations show the suitability of Stover Kincannon kinetic model to the anaerobic CSTR, which is capable of decreasing 50–75% COD at various OLR. The most appropriate fitting lines show the R<sup>2</sup> equals 0.9997, which are very close to unity and indicates the acceptability of model data. The considerable difference in the maximum removal rate constant (U<sub>max</sub>) (kg/m<sup>3</sup>/d) and the saturation value constant (K<sub>b</sub>) (kg/m<sup>3</sup>/d) values of this study and previous studies are observed. The difference in maybe because of the substantial variation in confined conditions between both the studies. Further, these constants may have different values for various OLRs, HRTs, and other operating

conditions of the digester. By adopting proper process models and consideration of microbial communities concerned in the removal of complex organic matter from wastewater, it is possible to avoid the problem of process stability. In the design and control of the treatment process of spent wash digestion, quality microbiological assessment study can help and play a vital role.

## Conclusions

The CSTR can effectively be adopted for the treatment of the spentwash. The maximum COD removal was found to be around 73% when operated in the favorable pH ranges. Optimum conditions for COD removal and biogas generation were found to be for OLR 0.10 kg/d to 0.11 kg/d, at 14d HRT, and VFA to Alkalinity ration around 0.12. Optimum biogas generation with a conversion coefficient of 0.405 was observed to be around 30L/d for steady-state conditions. The results show the applicability of the Stover Kincannon model to the reactor which is efficient to remove 70–75% COD at different OLR. Post-methanation effluent needs to be treated further. The performance towards COD reduction and Biogas formation can further be enhanced by increasing the buffering capacity of the reactor. Characterization of seed and or response of seed to micronutrients can also be required to focus. Using the modified Stover Kincannon kinetic model, the maximum removal rate constant ( $U_{max}$ ) and saturation value constant ( $K_b$ ) were observed to be 17.123 kg/m<sup>3</sup>/day, and 33.471 kg/m<sup>3</sup>/day. The outcomes show the utility of the Stover Kincannon model to the anaerobic CSTR. The performance of the digester can further be enhanced by adding micronutrients to the reactor; hence a microbiological study of seed culture needs to be conducted to analyze the performance.

## Abbreviations

1.	<b>BOD</b>	<b>Biochemical Oxygen Demand</b>
2.	COD	Chemical Oxygen Demand
3.	CSTR	Continuous Stirred Tank Reactor
4.	HLR	Hydraulic Loading Rate
5.	HRT	Hydraulic Retention Time
6.	$K_b$	Saturation Value Constant
7.	MLSS	Liquor Suspended Solids
8.	MoEF	Ministry Of Environment And Forests
9.	N	Nitrogen
10.	OLR	Organic Loading Rates
11.	P	Phosphorus
12.	Q	Flow Rate
13.	RSW	Raw Spent Wash
14.	S	Digester Substrate Concentration
15.	$S_e$	Effluent Organic Concentration
16.	$S_i$	Influent Organic Concentration
17.	UASBR	Anaerobic Sludge Blanket Reactor
18.	$U_{max}$	Maximum Removal Rate Constant
19.	TSS	Total Suspended Solids
20.	TDS	Total Dissolved Solids
21.	$U_{max}$	Maximum Removal Rate Constant
22.	V	Volume Of Rector
23.	VFA	Volatile Fatty Acids
24.	$\frac{dS}{dt}$	Substance Utilization Rate

## Declarations

### 1. Ethics approval and consent to participate:

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2. Not Applicable.

## 2. Consent for publication:

Not Applicable.

## 3. Availability of data and materials:

All data generated and analysed during this study are included in this article [and its supplementary information files].

## 4. Competing interests:

The authors declare that they have no competing interests

## 5. Funding:

Not Applicable.

## 6. Authors' contributions:

Dr. S. S. Salimath guided in analyzing the experimental data. Second authors have seen and approved the manuscript and have contributed significantly for the paper.

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# Figures

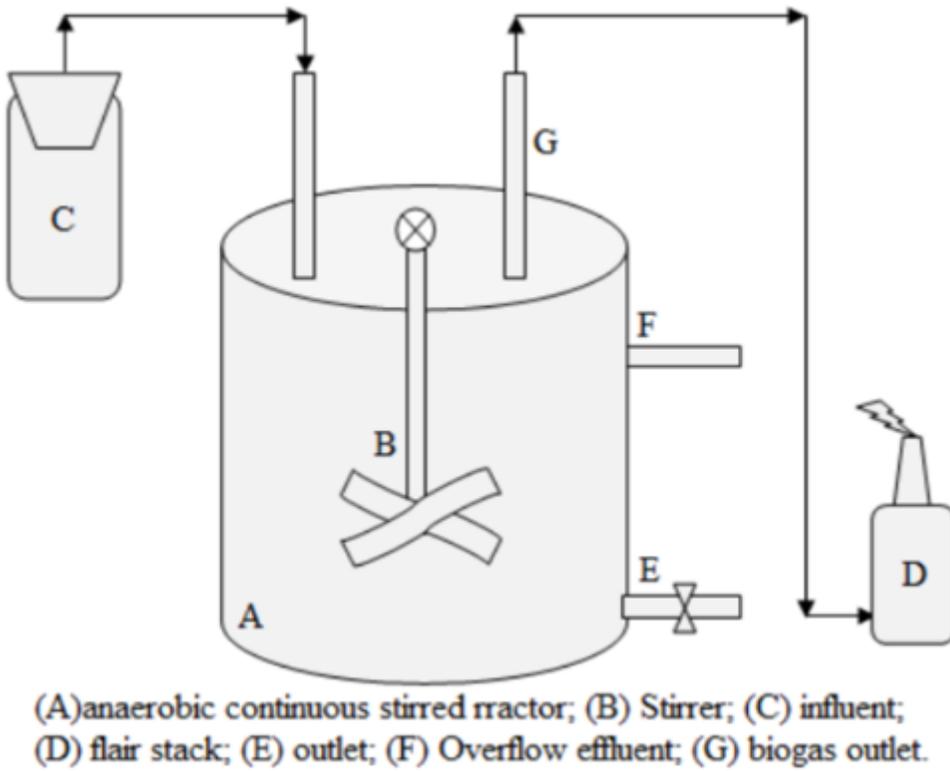


Figure 1

Schematic Arrangement of CSTR laboratory Model.

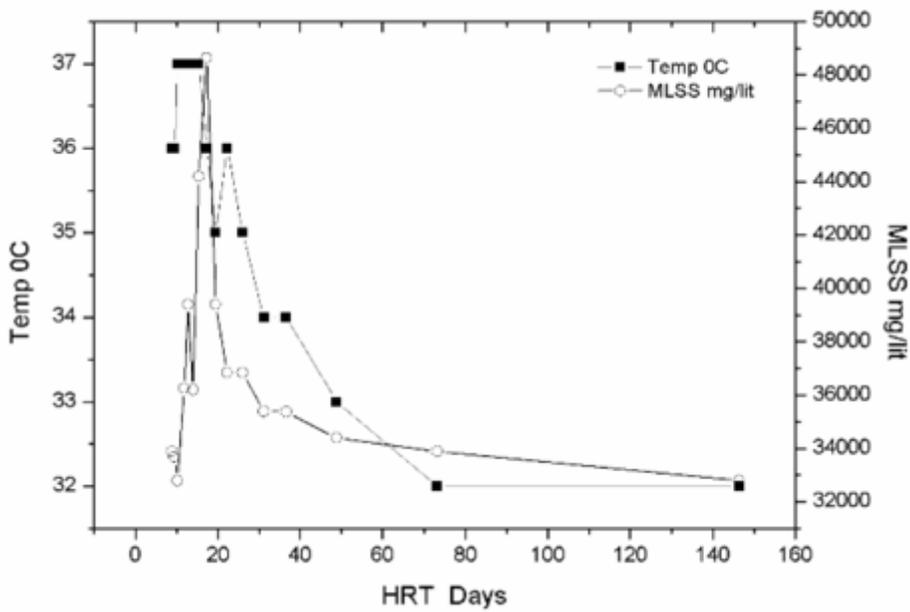


Figure 2

Variation of MLSS and Temperature with HRT.

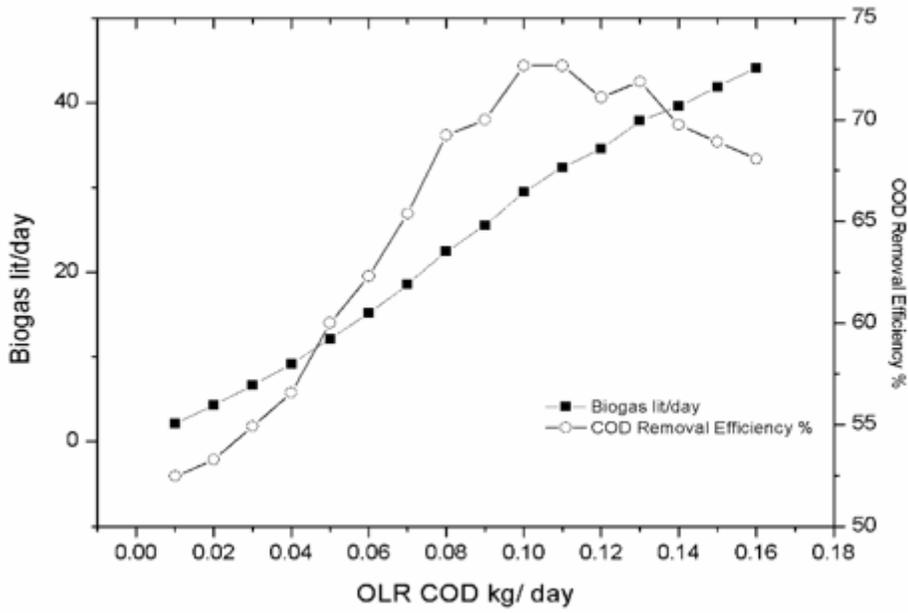


Figure 3

Effect of OLR on % COD reduction Biogas generation.

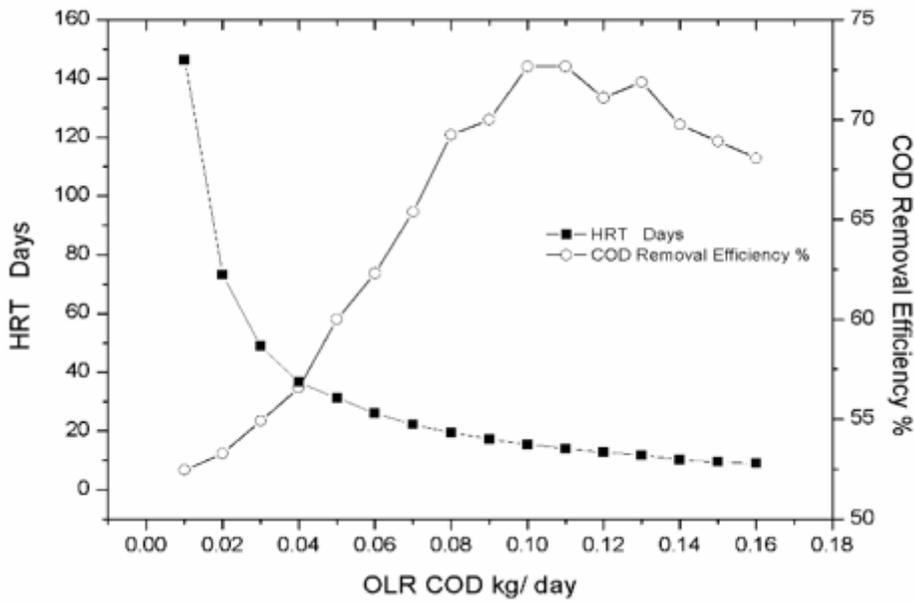


Figure 4

Effect of OLR and HRT on COD removal efficiency.

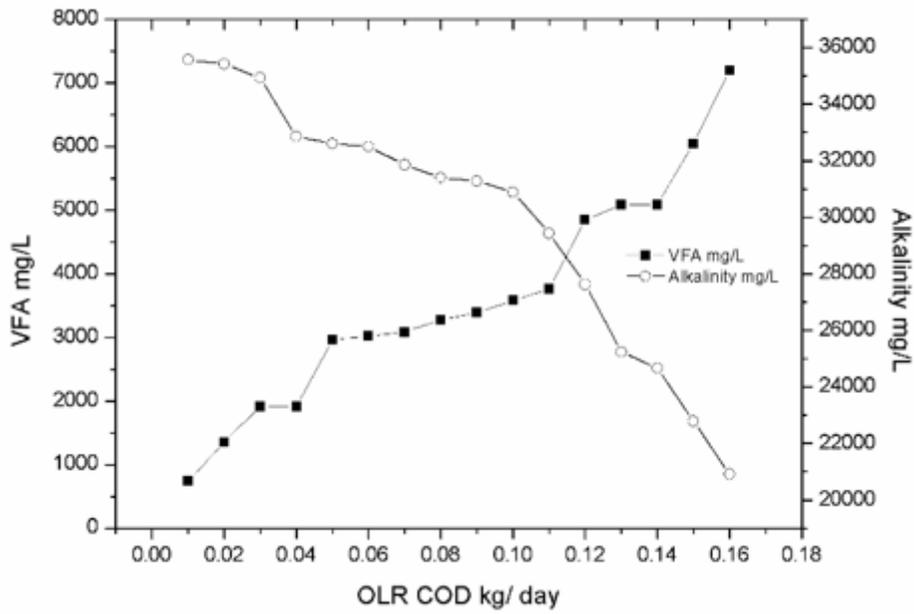


Figure 5

Effect of OLR on VFA and Alkalinity of digester.

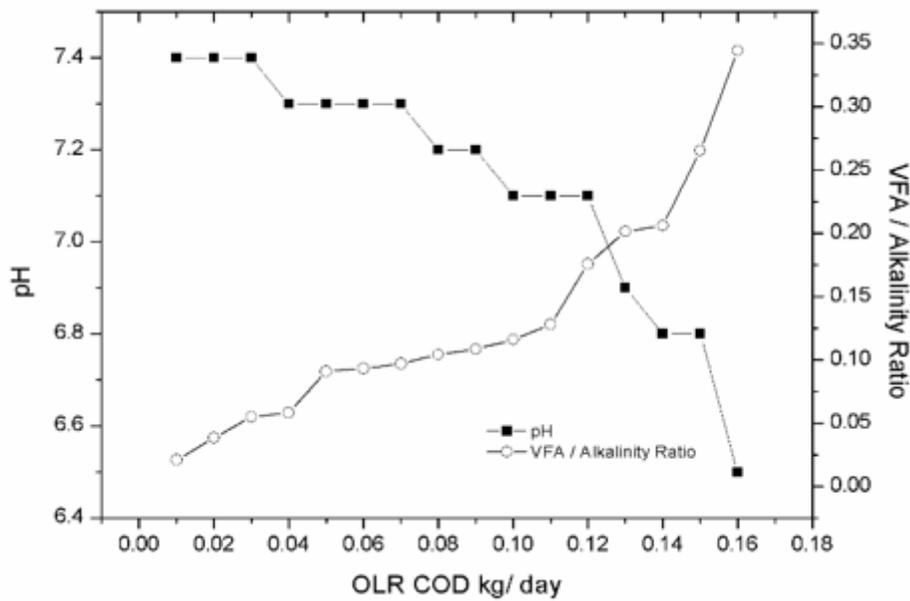


Figure 6

Variation of VFA to Alkalinity ratio and pH with OLR.

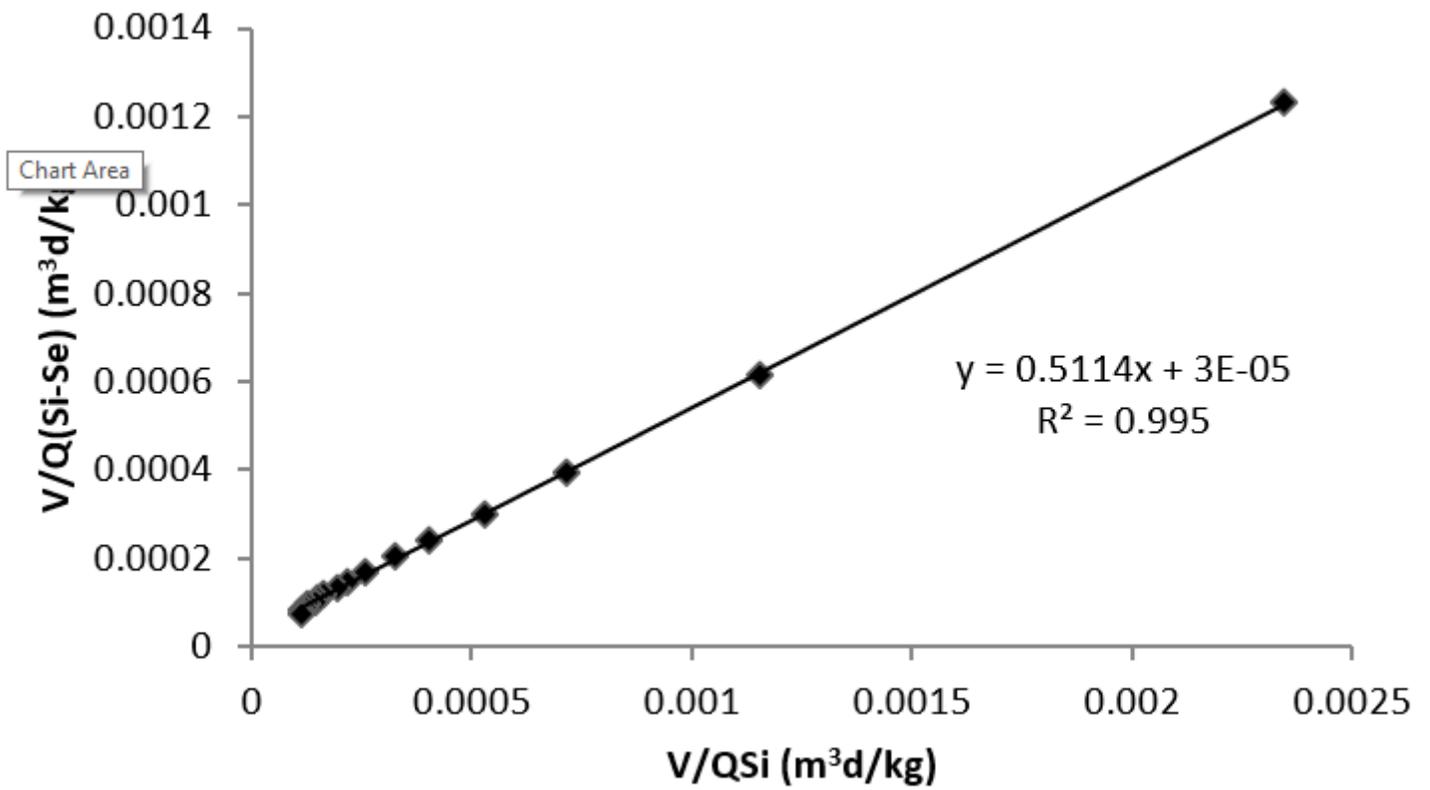


Figure 7

Stover and Kincannon model plot showing the effect of organic loading rate on rate of COD removal for CSTR lab model.

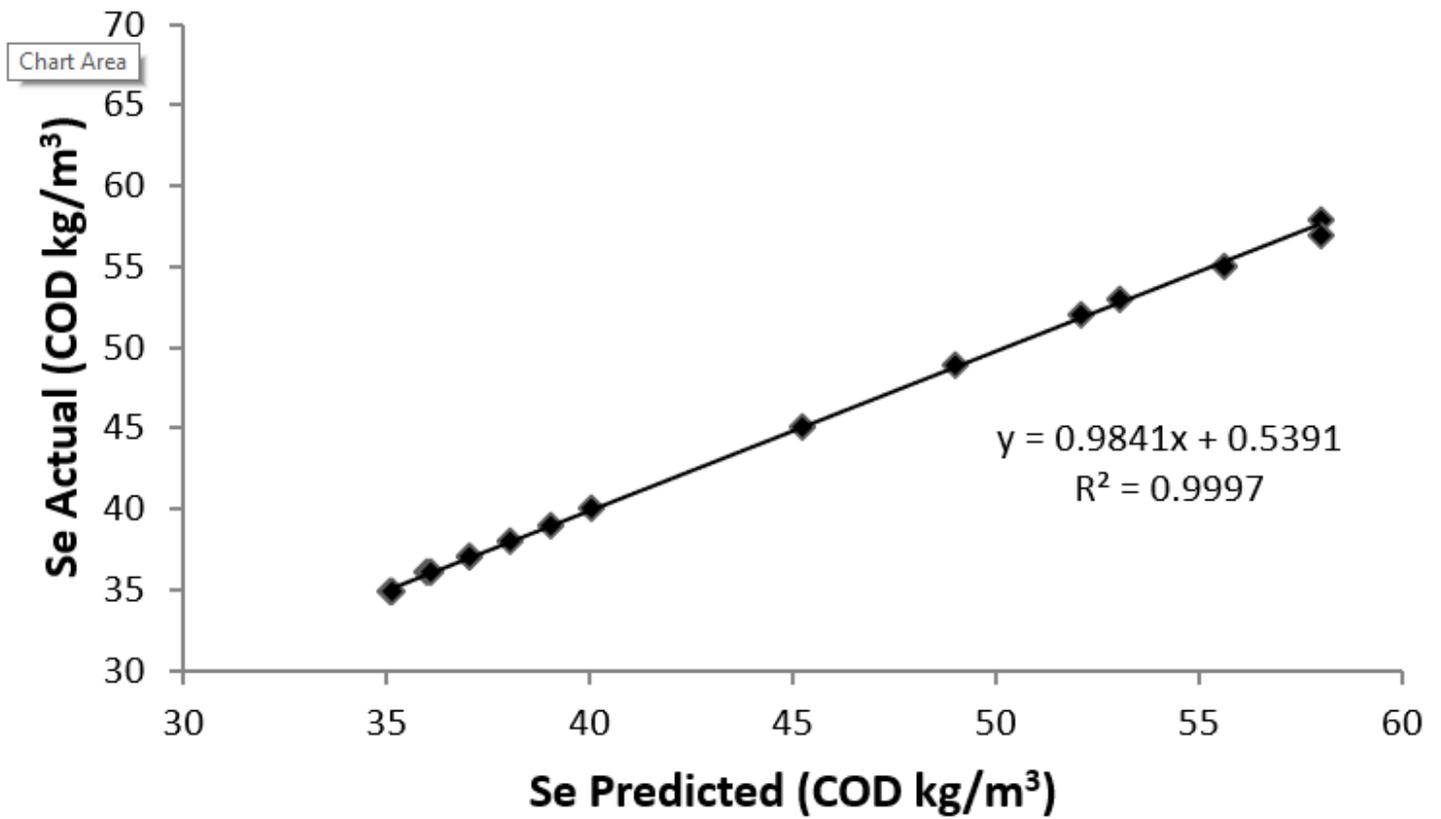


Figure 8

Relationship between (Se) predicted and (Se) observed for CSTR lab model.

## Supplementary Files

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