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DYNAMIC PERFORMANCE OF UPFLOW ANAEROBIC SLUDGE BLANKET REACTOR TREATING MUNICIPAL WASTEWATER AT LOW TEMPERATURE

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ABSTRACT
To explore the suitability of simple CSTR model for evaluating the dynamic performance of upflow anaerobic sludge blanket (UASB) reactor treating municipal wastewater at low temperature. The simultaneous dynamic equations for substrate and biomass mass were used to assess the UASB reactor performance of municipal wastewater. The dynamic model equations were solved by using a m.file in MATLAB2011a software command window and dynamic equations for substrate and biomass. The objectives of this paper are to evaluate the dynamic performances of UASB reactor treating municipal wastewater using the experimental results of Turkdogan-Aydinol et al. (2011).

KEYWORDS: CSTR model, Dynamic state, Mathematical Modelling, Substrate concentration.

INTRODUCTION
Low strength wastewater such as domestic sewage (COD concentration 500-1000 mg/L), are at present being treated anaerobically employing high rate anaerobic treatment system like UASB reactor. UASB reactor system is facing a challenge in the treatment of low- strength wastewater. Moreover, the formation of granular sludge with good settling characteristics and activity is a critical factor in dealing with low-strength wastewater (Singh and Viraraghavan 1998). It is apparent that, although much attention has given to the biochemistry and physical characteristics of anaerobic digestion, no systematic study are available in literature regarding the mathematical modelling of the granule size variation in UASB reactor treating low strength wastewaters. Further, not much effort made in the literature towards the evaluation of UASB reactor performance treating different low strength wastewaters using mathematical modelling approach. Therefore, a simple CSTR model has been applied and tested for its suitability to assess the dynamic performance of UASB reactor treating low strength wastewaters. To date, a large number of experimental studies have been conducted at laboratory, pilot plants and full-scale levels to study the treatability of a variety of wastes using UASB reactor. However, very few of these have been subjected to mathematical modelling and simulation. Most of the simulation efforts made so far have been concentrated towards the simplest type of effluents such as acetic acid or mixed volatile fatty acids (mixture of acetic, propionic and butyric acids) or lumping of all the volatile fatty acids into equivalent acetic acids. Little or no efforts are made till date to model the performance of UASB reactors treating low strength or municipal wastewaters, where granulation is difficult or achieved after a prolonged start-up. It is imperative that data pertaining to UASB reactor should be modelled so that a better insight can be obtained into the performance of UASB reactors treating low strength wastewaters. UASB reactor has been worldwide applied recently for treatment of low strength wastewaters during past 2 to 3 decades (Álveraz et al. 2006; Singh and Viraraghavan 1998; Das and Chaudhari 2009; Turkdogan-Aydinol et al. 2011; EL-Seddek et al. 2013; Bhatti et al. 2014; Lohani et al. 2015). Several attempts have been made in the recent past to the accelerate the granulation phenomenon in treatment of low strength wastewaters (Jeong et al. 2005; Sondhi et al. 2010). Some excellent experimental works on acceleration of the start-up period in treatment of low strength wastewater by UASB reactor are well reported in the literature (Jeong et al. 2005). But, there are little efforts made towards the modelling

and assessment of dynamic performances of UASB reactor treating low strength wastewaters (Agrawal et al. 1997; Alveraz et al. 2008; Kalyuzhnyi et al. 2006; Singh and Viraraghavan 1998; Turkdogan-Aydinol et al. 2011).
The main objectives of the present paper are: (1) to evaluate the kinetic constants for upflow anaerobic sludge blanket reactor treating municipal wastewaters using experimental results of Turkdogan-Aydinol et al. 2011 (2) to evaluate the dynamic performance of the UASB reactor treating low strength wastewaters using Monod kinetics for microbial growth and MATLAB2011a software, ode15s tool. The present paper devoted to explore the suitability of using a simple CSTR model for evaluating the dynamic performance of UASB reactor treating municipal wastewater. In case of treatment of municipal wastewaters (Turkdogan-Aydinol et al. 2011) where the stoichiometric relationships are not very clearly known/ available from literature, the simple model equations are derived for effluent waste COD and biomass concentrations. Determination of kinetic constants for low strength wastewater treatment in UASB reactor is necessary to predict the dynamic performances of the UASB system. Therefore, the kinetic constants (k, Ks, μ_{max}, Y and K_d) were determined using experimental results of Turkdogan-Aydinol et al. (2011) treating municipal wastewater in UASB reactor at low temperature.

MATERIAL AND METHODS

The rate of change of substrate and biomass in the system in words can be expressed as follows: [(Lokshina et al. 2000; Sponza 2001; Işik and Sponza 2005; Huang et al., 2006; Basu and Asolekar 2012; Yetilmezsoy 2012; and Rodríguez-Gómez et al. 2014)].

Net rate of accumulation of substrate within the reactor = input – output – rate of substrate consumption in the reactor. Mathematically, the mass balance equations on substrate and microorganisms given as Eqs. 1 and 2 simultaneously.

$$\frac{dS_e}{dT} = \frac{(S_o - S_e)}{\theta} - \frac{k.S_e.X_e}{(K_s + S_e)} \tag{1}$$

$$\frac{dX_e}{dT} = \frac{(X_o - X_e)}{\theta} + \left(\frac{Y.k.S_{e.}X_e}{(K_s + S_e)} - K_d.X_e \right) \tag{2}$$

If X_o is treated negligible (X_o=0), then Eq. (2) can be written as

$$\frac{dX_e}{dT} = \frac{(-X_e)}{\theta} + \left(\frac{Y.k.S_{e.}X_e}{(K_s + S_e)} - K_d.X_e \right) \tag{3}$$

The simultaneous dynamic equations for substrate and biomass were solved to assess the UASB reactor performance. The dynamic model equations were solved by developing a m.file in MATLAB2011a command window and writing the dynamic equations for substrate and biomass. Then, the experimental results of Turkdogan-Aydinol et al. (2011) were entered into Microsoft Excel Sheet and the file was imported by 'xlsread' tool in MATLAB2011a. By using, the initial conditions and the kinetic constants were programmed in m.file in MATLAB2011a. Programmed file, Excel sheet and equations of substrate and biomass m.file must be present in the same path of the system. Programmed m.file was then run by using ode15s tool of MATLAB2011a software and the solutions were obtained in command window of software.

RESULTS AND DISCUSSION

Determination of kinetic parameters

In order to proceed with the simulation of UASB reactor performance data, it is necessary to evaluate the kinetic constants, i.e., maximum substrate utilization rate (k) and half saturation constant (K_s), biomass yield coefficient (Y) and decay coefficient (K_d). On the basis of the principles of ideal CSTR assumption without sludge recycle (HRT =

SRT) and the following linear expressions can be obtained to evaluate the kinetic constants and re-written as (Matcalf and Eddy 1997).

$$\frac{\theta.X_e}{(S_o - S_e)} = \frac{K_s}{k}.\frac{1}{S_e} + \frac{1}{k} \tag{4}$$

$$\frac{(S_o - S_e)}{X_e} = \frac{K_d}{Y}.\theta + \frac{1}{Y} \tag{5}$$

Further, for the steady state condition when X_o taken into account the linear expressions represented by Eqs. (4) and linear Eq. (6) as given below were used to evaluate the kinetic constants.

$$\frac{(X_o - X_e)}{\theta.X_e} = -Y\frac{(S_o - S_e)}{\theta.X_e} + K_d \tag{6}$$

Where, θ is the hydraulic retention time (d) and SRT is the solid retention time (d). Using linear regression of the experimental data and using Eqs. (4) and (5), the kinetic parameters are determined. The kinetic constants k and K_s were determined from the slope and intercept of straight-line plot shown in figure 1 and the biomass yield coefficient (Y) and microorganism's decay coefficient (K_d) were determined from the slope and intercept of straight line plot shown in figure 2. The values of the kinetic constants are given in Table 1 later. When the influent biomass concentration (X_o) is taken into account, the values of kinetic constants k and K_s were obtained from Eq. (1) as shown in figure 1. The kinetic constants to be used in assessment of UASB reactor performance, the linear equations (4) and (5) were used, which are given below when influent biomass concentration (X_o) is negligible. The kinetic constants k and K_s were determined from the slope and intercept of the straight-line plot between $\theta.X_e / (S_o\text{-}S_e)$ and $1/S_e$ as per Eq. (4). Other kinetic constants Y and K_d were determined from the slope and intercept of straight line plot between $(S_o\text{-}S_e)/ X_e$ and θ as per Eq. (5).

Turkdogan-Aydinol et al. (2011) investigated the UASB performance evaluation and kinetic modelling of the start up of UASB reactor treating municipal wastewater at low temperatures. A 10 L plexiglass UASB reactor was operated for 105 days at three different HRTs of 1, 0.5 and 0.208 days. Average organic loading rate was reported from 0.57-11.71 kg TCOD/m^3.d.

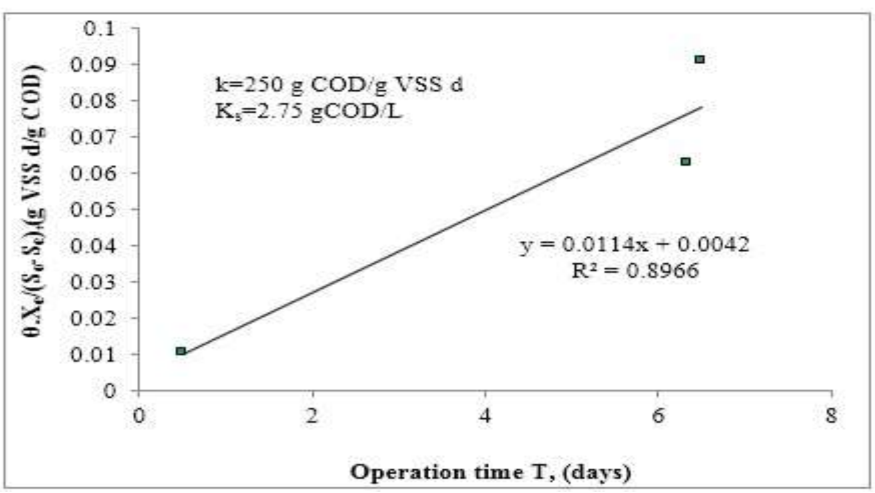

Figure 1: Determination of maximum substrate utilisation rate (k) and half saturation constant (K_s) using experimental results of Turkdogan-Aydinol et al. (2011)

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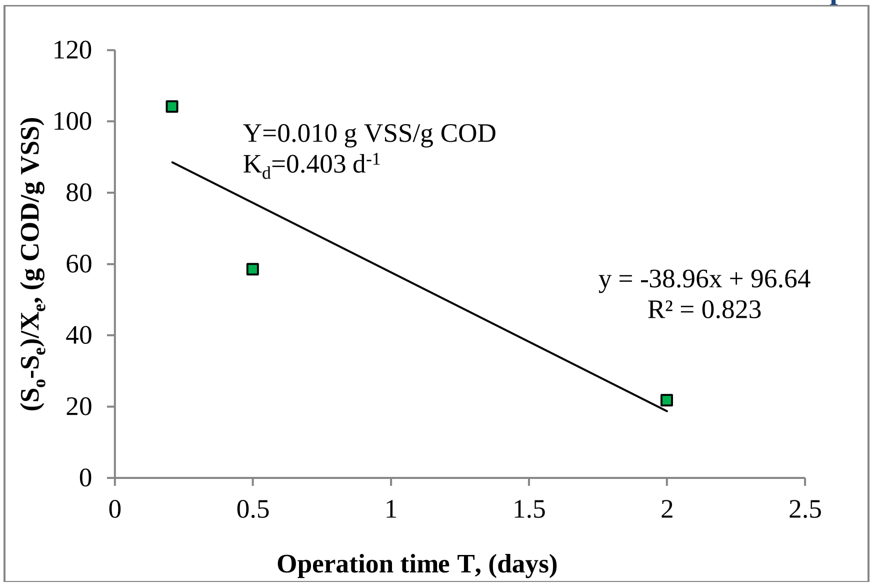

Figure 2: Determination of biomass yield coefficient (Y) and microorganism's decay coefficient (K_d) (when X_o negligible) using experimental results of Turkdogan-Aydinol et al. (2011)

The linear fitting of Eqs. (4) and (5) are shown in figures 1 and 2 respectively when X_o is negligible. In these figures, only 3 data points are seen as the reactor was operated only at three different HRTs. Relatively a poor linear fitting (low R^2- values) can be seen in both the figures (1) and (2). Hence, the computed kinetic constants may not represent a true value and may result in poor simulation of UASB reactor performance. The kinetic constants evaluated from these figures are reported in Table 1 for the case when X_o is considered negligible.

The kinetic constants were also computed for the case when X_o is accounted as per Eqs. (4) and (6). The linear plots as per Eq. (4) is shown in figure (1) while as per Eq. (6) is shown in figure 3. The kinetic constants are presented in Table 1.

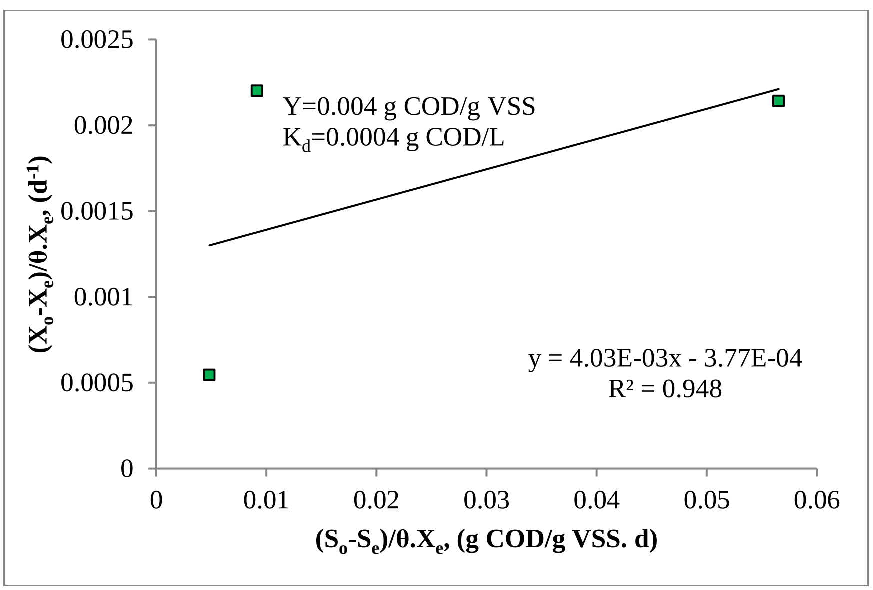

Figure 3: Determination of biomass yield coefficient (Y) and microorganism's decay coefficient (K_d) influent biomass concentration is considered using experimental results of Turkdogan-Aydinol et al. (2011)

In order to evaluate the kinetic constants Y and K_d when influent biomass concentration (X_o) is accounted, the linear plot as per Eq. (6) is shown below in figure 3 with poor R^2-value of 0.948. The evaluated values of kinetic constants i.e., Y and K_d are presented in Table 1, when X_o is accounted. The kinetic constants evaluated from all these figures are presented in Table 1.

Table 1: Evaluation of kinetic constants using the experimental result of Turkdogan-Aydinol et al. (2011)

Reference/source		**k (g. COD/g.VSS.d)**	**K_s (g. COD/L)**	**Y (g.VSS/g.COD)**	**K_d (d^{-1})**	**μ_{max} (d^{-1})**
Turkdogan-Aydinol et al. (2011)	X_o is negligible	250	2.75	0.010	0.403	2.50
	X_o is accounted	250	2.75	0.004	0.0004	1.0

Evaluation of dynamic performance using experimental results of Turkdogan-Aydinol et al. (2011)

The experimental results of Turkdogan-Aydinol et al. (2011) for dynamic period of 105 days, reported at 10 days intervals are used for dynamic simulations for cases when X_o is negligible and X_o is accounted. The experimental results for steady state period are not available in the research work of Turkdogan-Aydinol (2011) as total operation period was 105 days only during which the reactor was under dynamic conditions. Due to this reason, steady state data are not presented here.

Table 2: Experimental results of Turkdogan -Aydinol et al. (2011) for evaluation of dynamic performance

S.No.	**θ, (days)**	**Time (days)**	**S_o**	**X_o**	**S_e**	**X_e**
1-	2	10	0.615	0.073	0.154	0.021
2-	0.5	20	0.257	0.072	0.101	0.022
3-		30	0.29	0.072	0.16	0.021
4-		40	0.349	0.072	0.158	0.024
5-	0.208	50	0.27	0.101	0.2	0.027
6-		60	0.277	0.178	0.172	0.027
7-		70	1.28	0.212	1.22	0.022
8-		80	2.81	0.091	2.68	0.026
9-		90	2.5	0.09	2.41	0.029
10-		100	2.5	0.083	2.01	0.024

Note: θ - Hydraulic retention time (days); S_o- Influent COD concentration (g.COD/L); S_e- Effluent COD concentration (g.COD/L); X_o- influent biomass concentration (g VSS/L); X_e- Effluent biomass concentration (g.VSS/L)

Evaluation of dynamic performance using experimental results of Turkdogan-Aydinol et al. (2011) when influent biomass concentration (X_o) is negligible

Using the experimental results of Turkdogan-Aydinol et al. (2011**)** on treatment of the municipal wastewater from Table 2 for a transient period of 105 days and kinetic constants from Table 1, the dynamic equations (1) and (3) were solved simultaneously for effluent soluble COD concentration (S_e) and effluent biomass concentration (X_e) using MATLAB2011a, ode15s tool with a time step of 10 days. A large step size of 10 days was taken due to large fluctuations in the experimental results of Turkdogan-Aydinol et al. (2011**)** during initial phases of operation.

Prediction of dynamic performance in terms of effluent COD concentration (S_e)

The results of simulations of effluent COD (S_e) and effluent biomass (X_e) concentrations at 10 days intervals are presented in Table 3. The percentage error in predicted and experimental effluent COD (S_e) and effluent biomass concentrations (X_e) are also computed and presented in table 3.

Table 3: Percentage error between experimental and predicted effluent COD and biomass concentrations during dynamic phase using experimental results of Turkdogan-Aydinol et al. (2011) (X_o negligible)

Time	θ, (days)	S_e (Exp.)	S_e (Pred.)	% Error	X_e (Exp.)	X_e (Pred.)	% Error
10	2	0.154	1.039	574.67	0.021	0.097	361.90
20	0.5	0.101	0.017	82.97	0.022	0.073	235.16
30	0.5	0.16	0.024	84.49	0.021	0.080	284.80
40	0.5	0.158	0.027	82.43	0.024	0.081	239.72
50	0.208	0.2	0.033	83.30	0.027	0.081	202.80
60	0.208	0.172	0.050	70.46	0.027	0.090	234.32
70	0.208	1.22	0.052	95.72	0.022	0.090	310.57
80	0.208	2.68	0.227	91.50	0.026	0.092	257.67
90	0.208	2.41	0.542	77.49	0.029	0.097	235.83
100	0.208	2.01	0.479	76.14	0.024	0.096	302.46

Percentage error in prediction of effluent COD and biomass concentrations varies from 70.46% to 574.67% and 235.16% to 361.90% respectively, which shows a very large error in predictions, hence simple steady state CSTR model equations are not suitable for the evaluation of UASB reactor performance in the present case as well. Variation of predicted effluent soluble COD and experimental effluent soluble COD concentrations as a function of operation time are shown in figure 4 and that for effluent biomass concentrations are shown in figure 5.

From both the figures 4 and 5, it is evident that there is a large deviation of predicted values in comparison to their corresponding experimental values. Predicted and experimental effluent COD concentrations show bit close results between 20 to 60 days of operation.

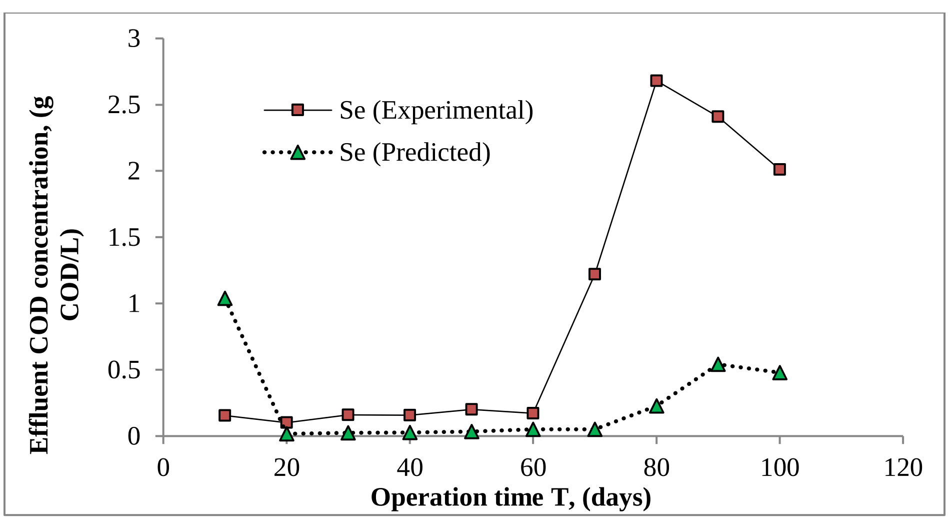

Figure 4: Agreement between the predicted effluent soluble COD and the experimental effluent COD concentrations at different operation time during dynamic phase using the experimental results of Turkdogan-Aydinol et al. (2011) (X_o negligible)

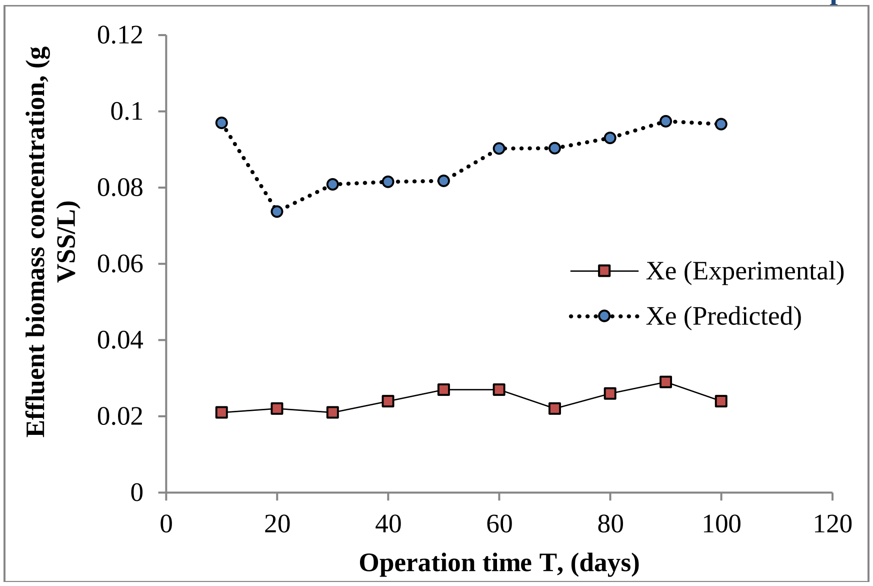

Figure 5: Agreement between the predicted effluent biomass and the experimental effluent biomass concentrations at different operation time during dynamic phase using the experimental results of Turkdogan-Aydinol et al. (2011) (X_o negligible)

Therefore, the overall results of simulation don't agree well with the experimental results and therefore, the application of Eqs. (1) and (3) in simulation of dynamic performance of UASB reactor seems to be inappropriate with very limited accuracy. Therefore, dynamic simulation using simple CSTR model is not suitable to simulate effluent COD and biomass concentrations in UASB reactor in the present case, when X_o is negligible.

Evaluation of dynamic performance in terms of effluent COD and effluent biomass concentrations using experimental results of Turkdogan-Aydinol et al. (2011) (X_o accounted)

Using the experimental results of Turkdogan-Aydinol et al. (2011) on the treatment of the municipal wastewater given in Table 2 for a transient period of 105 days, the dynamic equations (1) and (2) were solved simultaneously for effluent soluble COD concentration (S_e) and effluent biomass concentration (X_e) using MATLAB2011a software, ode15s tool with time step of 10 days, when X_o is accounted. The results of simulations of effluent COD and effluent biomass at 10 days intervals are presented in Table 4. The percentage error in predicted and experimental effluent COD (S_e) and effluent biomass concentrations (X_e) are also presented in table 4. Percentage error in prediction of effluent COD and biomass varies from 79.13 % to 98.65 % and 202.80 % to 284.80% respectively. From both the figures, it is evident that predicted values are largely deviated from their corresponding experimental values and clearly demonstrate the non-suitability of simple CSTR model in the present simulation where X_o is accounted. The statistical error estimates are not computed due to large errors in prediction. Variation of predicted effluent soluble COD concentration and experimental effluent soluble COD concentrations as a function of operation time are shown in figure 6 and that for effluent biomass concentrations a shown in figure 7. From both the figures 6 and 7, it is evident that there is a large deviations of predicted values in comparison to their corresponding experimental values. Predicted and experimental effluent COD concentrations show bit close results between 20 to 60 days of operation.

Table 4: Percentage error between experimental and predicted effluent COD and biomass concentrations during dynamic phase using experimental results of Turkdogan-Aydinol et al. (2011) (X_o accounted)

Time	θ, (days)	S_e (exp.)	S_e (Pred.)	% Error	X_e (exp.)	X_e (Pred.)	% Error
10	2	0.154	0.154	0	0.021	0.021	0
20	0.5	0.101	0.010	89.22	0.022	0.073	235.16
30	0.5	0.16	0.014	90.87	0.021	0.080	284.80

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40	0.5	0.158	0.013	91.45	0.024	0.081	239.72
50	0.208	0.2	0.013	93.31	0.027	0.081	202.80
60	0.208	0.172	0.035	79.13	0.027	0.090	234.32
70	0.208	1.22	0.063	94.78	0.022	0.090	310.57
80	0.208	2.68	0.075	97.16	0.026	0.092	257.67
90	0.208	2.41	0.032	98.65	0.029	0.097	235.83
100	0.208	2.01	0.031	98.41	0.024	0.096	302.46

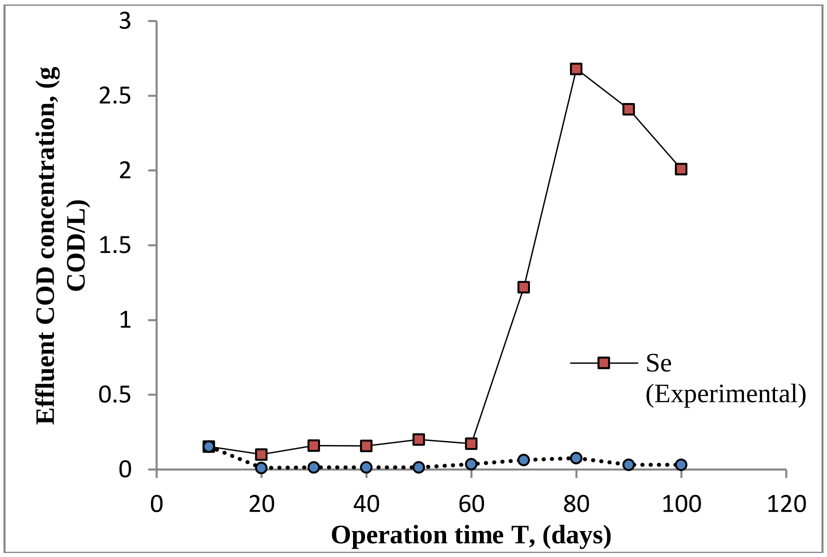

Figure 6: Agreement between the predicted effluent soluble COD and the experimental effluent COD concentrations at different operation time during dynamic phase using the experimental results of Turkdogan-Aydinol et al. (2011) (X_o accounted)

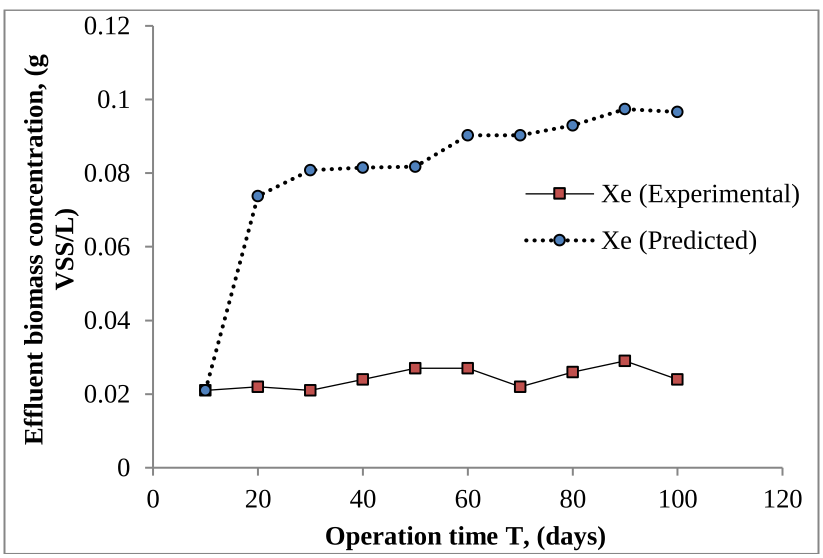

Figure 7: Agreement between the predicted effluent biomass and the experimental effluent biomass concentrations at different operation time during dynamic phase using the experimental results of Turkdogan-Aydinol et al. (2011) (X_o accounted)

Therefore, the overall results of simulation don't agree well with the experimental results and therefore, the application of Eqs. (1) and (2) in simulation of dynamic performance of UASB reactor seems to be inappropriate with very limited accuracy. Therefore, dynamic simulation using simple CSTR model is not suitable to simulate effluent COD and biomass concentration in UASB reactor in the present case, when X_o is accounted.

CONCLUSION

The kinetic constants required for prediction of performances in terms of effluent COD concentration (S_e) and effluent biomass concentration (X_e) are evaluated and presented using experimental result of Turkdogan-Aydinol et al. (2011) treating municipal wastewater at low temperature in UASB reactor. A simple CSTR model for evaluation of UASB reactor performance developed by considering the flow regime in UASB reactor as completely stirred tank reactor (CSTR) with or without consideration of influent biomass concentrations in the influent stream. Linear equations derived for the evaluation of kinetic constants for their use in model equations. The evaluation of dynamic performance of UASB reactors treating municipal wastewater were carried out by using experimental results of Turkdogan-Aydinol et al. (2011). From the results, it concluded that a simple CSTR model is inappropriate for the evaluation of dynamic performances of UASB reactors treating municipal wastewater as the errors in predictions were obtained too large with respect to their corresponding experimental values.

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