ORIGINAL PAPER

Kinetic modeling of carbon and nutrients removal in an integrated rotating biological contactor-activated sludge system

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Abstract In this study, kinetics of biological carbon, nitrogen, and phosphorous removal from a synthetic wastewater in an integrated rotating biological contactor-activated sludge system was investigated. The experimental data obtained from varying four significant independent factors viz., hydraulic retention time, chemical oxygen demand for nitrogen to phosphorus ratio, internal recirculation from aerobic to anoxic zone and disks rotating speed were used for the process kinetic modeling. In order to obtain the bioprocess kinetic coefficients, Monod, first-order and Stover–Kincannon models were employed. As a result, Monod and Stover–Kincannon models were found to be the appropriate models to describe the bioprocess in the rotating biological contactor-activated sludge system as the determination coefficient for the first-order model obtained less than 0.79. According to the Monod model, growth yield, microbial decay rate, maximum specific biomass growth rate, and half-velocity constant coefficients were found to be 0.712 g VSS/g COD, 0.008/d, 5.54/d and 55 mg COD/L, respectively. From Stover–Kincannon model, the maximum total substrate removal rate constant and half-velocity constant were determined as 15.2, 10.98, 12.05 g/L d and 14.78, 7.11, 6.97 mg/L for chemical oxygen demand, nitrogen and phosphorus removal, respectively. The kinetic parameters determined in this study can be used to improve the design and operation of the biological contactor-activated sludge system in full scale.

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List of symbols

RBC	Rotating biological contactor
AS	Activated sludge
TKN	Total Kjeldahl nitrogen, mg/L
MLSS	Mixed liquor suspended solids, mg/L
COD	Chemical oxygen demand, mg/L
TN	Total nitrogen, mg/L
VSS	Volatile suspended solid, mg/L
SRT	Solid retention time, d^{-1}
OLR	Organic loading rate, g/L d
Y	Growth yield coefficient, g VSS/g COD
k_d	Microbial decay rate, d^{-1}
μ_{max}	Maximum specific biomass growth rate, g VSS produced/g VSS present d
k_s	Half-velocity constant, mg/m^3

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U_{max}	Maximum substrate utilization rate constant, g/L d
r_{su}	Rate of change in the substrate concentration due to utilization, g/m³ d
r_g	Rate of change in the biomass concentration, g/m³ d
K	Maximum specific substrate utilization rate, g COD/g VSS prod. d
X	Biomass concentration, g/m³
S_0	Influent substrate concentration, g/m³
S	Substrate concentration, g/m³
μ	Specific biomass growth rate, g VSS produced/g VSS present d
k_1	First-order nitrogen removal rate constant, d^{-1}
Q_0	Influent flow rates, m³/d
Q	Effluent flow rates, m³/d
Q_w	Waste sludge flow rates, m³/d
X_e	Effluent biomass concentration, mg/L
X_w	Effluent biomass concentration, mg/L
V	Volume of the reactor, m³
r_{su}/x	Specific substrate utilization rate, g COD/g VSS d
ds/dt	Substrate removal rate, g/L d

Introduction

Biological carbon, nitrogen, and phosphorus removal from wastewater has become a common requirement of wastewater treatment (Brdjanovic 1998). Biological removal of nutrients (N and P) and carbonaceous matter is often carried out by integrating anaerobic, anoxic and aerobic biological processes. Systems like A/O and A²/O are typical examples of this integration; different treatment systems are being developed to maximize the advantages of both aerated and non-aerated processes (Santos et al. 1998). The rotating biological contactor (RBC) is widely used in wastewater treatment as an efficient attached growth system. RBCs are easy to operate, have a short start-up, require little maintenance, are effectively oxygenated with little sloughing of biomass, and have low energy consumption (Pathwardan 2003). RBCs have been used for treating domestic and industrial wastewaters, amenable to aerobic biological oxidation, for accomplishing varied degrees of carbonaceous and or nitrogenous oxygen demand reductions (Metcalf and Eddy 2003).

Process modeling can be used to describe and simulate the performance of these and other biological processes. The knowledge of process kinetics provides a rational basis for process analysis and control. It also helps to determine the effects of operational and environmental factors on substrate utilization rates. It is possible to optimize reactor performance based on kinetics study. Some commonly used

models for describing organic removal in bioreactors include Monod, first order substrate removal model and Stover–Kincannon model (Palma and Verdone 2009). The model kinetic coefficients give the reaction rates of the system and provides a basis for reactor design and operation.

In a previous study (Akhbari et al. 2011), nutrients removal using an integrated rotating biological contactor-activated sludge (RBC-AS) system was conducted. The system was found to be effective in the removal of organic matter and nutrients. Chemical oxygen demand (COD), total nitrogen (TN) and phosphorus (TP) removals under optimized conditions was 85–87%, 58–74% and 58–87%, respectively. This study uses the Monod, first-order kinetic, and Stover–Kincannon model to determine the COD, TN and TP removal biokinetic parameters for the RBC-AS system.

Materials and methods

Composition of synthetic wastewater (SWW)

Synthetic wastewater was prepared based on the three different COD:N:P ratios (1,000:250:50, 1,000:83.3:35 and 1,000:50:20). Glucose, NH_4Cl and KH_2PO_4 were used as sources of carbon, nitrogen and phosphorus, respectively. Characteristics of the SWW are shown in Table 1.
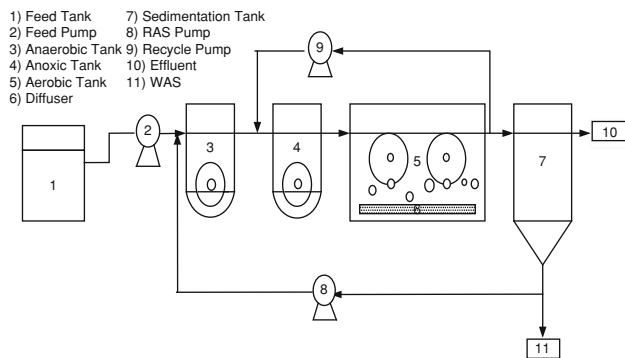
Experimental set-up

The three-stage RBC-AS system consisted of an anaerobic (R_1), anoxic (R_2) and an aerobic reactor (R_3) made of Plexiglas. Figure 1 shows a sketch of the experimental set-up (Akhbari et al. 2011). The covered anaerobic and anoxic units each had a 2.85 l working volume and 12 fully immersed biodisks with 12 cm diameter. The biodisks were connected to a motor via a stainless steel shaft and rotated at 5–15 rpm parallel to the direction of wastewater flow. In order to supply sufficient mixing, four 2-cm rectangular blades were placed on the disks. Two variable-

Table 1 Characteristics of synthetic wastewater

Parameter	Concentration (mg/L)
TCOD = SCOD	1,070–1,110
BOD	980–1,040
TN	65–270
TP	20–50
NO_3^-	15–20
$NaHCO_3$	0.5–2

Values are average of three measurements. The differences between the measurements for each were less than 1%

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Fig. 1 Sketch of the experimental set-up (Akhbari et al. 2011)

speed peristaltic pumps were used to feed the anaerobic unit and recycle effluent from the aerobic unit to the anoxic unit in order to promote denitrification. A 6-L settling tank was provided to collect the washed out biomass for recycling to the anaerobic unit using a centrifuge pump. Excess sludge was wasted. The average dissolved oxygen (DO) levels were 0.05, 0.1, 5.2 mg/L in the anaerobic, anoxic and aerobic units, respectively.

Bioreactor operation

The study was conducted for a period of 10 months in 2009–2010. The reactor was initially inoculated with activated sludge taken from an aeration tank (municipal wastewater treatment plant, Kermanshah, Iran). The inoculum sludge had a sludge age of about 15 days and a mixed liquor suspended solids (MLSS) concentration of 5.8 g/L. After initial dilution, 2.5-L activated sludge was seeded to the reactor, resulting in an initial MLSS concentration of 3.8–4.0 g/L in the reactor. The reactor start-up involved daily feeding of synthetic wastewater until biofilm started to form on the disks after 3 weeks, especially in the aerobic unit, and the reactors were thereafter operated in series in a continuous flow test mode. During the system operation period, the biomass attached to the rotating disks and suspended in the mixed liquor in the three RBC units was collected, dried, weighed and characterized for three times. Based on the measurements, the attached biomass in the anaerobic and anoxic units was found to be less than 20% of the total MLSS, while it was between 30 and 40% for the aerobic unit. The time of each experiment was dependent on the HRT and steady state was assumed after five turnovers.

Analytical techniques

The following parameters were analyzed according to the Standard Methods (APHA et al. 1999): COD, total Kjeldahl nitrogen (TKN), NO_3^-, TP, pH, MLSS and volatile suspended solid (VSS). For COD, spectrophotometer (DR 5000,

Hach, Jenway, USA) was used. Total Kjeldahl nitrogen was determined by TKN meter Gerhardt model (vapodest10). The dry weight of the attached biofilm per unit wetted surface area of the disk was determined by removing the attached biofilm from 1 cm^2 of the disk and drying at 80°C for 24 h. DO concentration in the wastewater was determined using a DO meter; WTW DO Cell OX 330, electro DO probe, Germany.

Mathematical modeling

Mass balance-based (Monod) model

For soluble substrate, the substrate utilization rate in biological systems can be modeled with the following expression (Weng and Molof 1974):

$$r_{su} = -\frac{ds}{dt} = \frac{kSX}{K_s + S} \tag{1}$$

where, K_s stands for half-velocity constant.

The biomass growth rate is proportional to the substrate utilization rate by the yield coefficient, and the biomass decay is proportional to the amount of biomass present. When the substrate is being consumed at its maximum rate, the bacterial growth rate is also at its maximum (Jin and Zheng 2009). By substituting ($k = \mu_{max}/Y$) in Eq. (1), the expression will change to

$$r_{su} = \frac{\mu_{max}XS}{Y(K_s + S)} \tag{2}$$

where Y and μ_{max} indicate growth yield and maximum specific biomass growth rate.

Taking into consideration, influent and effluent substrate concentration:

$$Q_0S_0 = QS + \frac{1}{Y}\left(\frac{\mu_{max}XS}{K_s + S}\right)V \tag{3}$$

and also,

$$r_g = \frac{dx}{dt} = -Y\left(\frac{ds}{dt}\right) - kdX = Y\left(\frac{kXS}{K_s + S}\right) \tag{4}$$

Dividing both sides of Eq. (4) by the biomass concentration X, the specific growth rate was:

$$\frac{r_g}{X} = \mu = Y\left(\frac{K_s}{K_s + S}\right) - k_d \tag{5}$$

where K_d express microbial decay rate.

The specific biomass growth rate (μ) can be defined as inverse of the solid retention time (SRT).

$$\frac{1}{SRT} = (Q - Q_w)X_e + \frac{Q_wX_w}{VX} \tag{6}$$

Thus, Eq. (4) can be rearranged as follows:

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$$\frac{1}{\text{SRT}} = -Y\left(\frac{r_{\text{su}}}{X}\right) - k_{\text{d}} = \frac{YQ(S_0 - S)}{VX} - k_{\text{d}}. \qquad (7)$$

First-order substrate removal model

Assuming that first-order kinetics prevails in the reactor, the rate of change in substrate concentration in a completely mixed system could be expressed as under (Jin and Zheng 2009):

$$-\frac{dS}{dt} = \frac{QS_0}{V} - \frac{QS}{V} - k_1 S \qquad (8)$$

Under pseudo steady-state conditions, the rate of change in substrate concentration $(-dS/dt)$ is negligible and Eq. (8) can be modified as:

$$\frac{S_0 - S}{\text{HRT}} = k_1 S \qquad (9)$$

Thus, the value of k_1 can be obtained by plotting $[(S_0 - S)/\text{HRT}]$ versus S.

Stover–Kincannon model

The Stover-Kincannon model was initially used to predict the attached growth biomass performance in a rotating biological contactor. Later, the model was modified and widely applied to describe and predict the performance of other types of bioreactors (Stover and Kincannon 1982; Isik and Sponza 2005; Kapdan and Aslan 2008). The original model is represented by Eq. (10).

$$\frac{ds}{dt} = \frac{Q}{V}(S_0 - S) \qquad (10)$$

where dS/dt is defined as follows:

$$\frac{ds}{dt} = \frac{U_{\text{max}}\left(\frac{QS_0}{V}\right)}{K_s + \left(\frac{QS_0}{V}\right)} \qquad (11)$$

$$\frac{1}{\left(\frac{ds}{dt}\right)} = \frac{V}{Q(S_0 - S)} = \frac{K_s V}{U_{\text{max}} Q S_0} + \frac{1}{U_{\text{max}}} \qquad (12)$$

If $V/[Q(S_0 - S)]$, which is the inverse of the total substrate removal rate plotted against the inverse of the total substrate loading rate (V/QS_0), the kinetic constants U_{max} and K_s can be determined.

Results and discussion

Model development

Mass balance-based (Monod) model

The Monod model is the most widely used model for different reactors and wastewaters (Monod 1949; Borja et al.
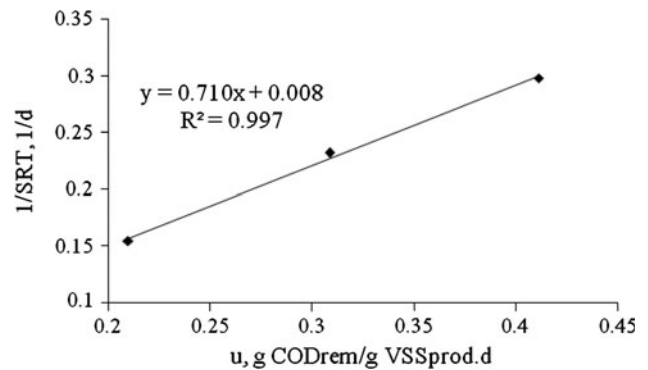
Fig. 2 Specific microbial growth rate versus specific substrate utilization rate for COD removal at influent

2003). The kinetic coefficients (μ_{max} and K_s) were computed using the mass balance equation (Eq. 3) in Sigma plot Software, ver. 6. In order to estimate the biomass decay coefficient (k_d), the relationship between the inverse SRT and the specific substrate utilization rate ($-r_{\text{su}}/X$) (Eq. 7) for COD was plotted (Fig. 2). The data used for the kinetic modeling are the average of the performance data presented in Table 2 at different HRTs. All kinetic coefficients obtained from the models are summarized in Table 3. The kinetic parameters (for COD removal), μ_{max} and K_s were obtained as 5.54/d and 55 mg COD/L, respectively. This model could not be fitted with the TN and TP data at high determination coefficient (R^2).

First-order model

The nitrogen removal kinetics was modeled by the first-order model. The first-order kinetic constant, k_1, was calculated by plotting $(TN_0 - TN)/\text{HRT}$ versus TN from Table 2. From Fig. 3, the kinetic coefficient (k_1) was determined to be 1.882/d with the R^2 of 0.792. The model did not show a good agreement with the data obtained for COD and P removal.

Stover–Kincannon model

Another model that was employed for kinetic modeling of COD, N and P removal in the RBC-AS system is the Stover–Kincannon model. This model is similar to the Monod model with this difference that organic loading is used instead of concentration. Figure 4a–c shows the linearized plots obtained for each constituent (COD, N and P). Linear regression was used to determine the intercept and slope. k_s and U_{max} for COD, N and P removal were calculated to be 14.78, 7.11, 6.97 mg/L and 15.2, 10.98, 12.05 g/L d, respectively. The correlation coefficients for COD, N and P removal were found to be 0.813, 0.960, and 0.844, respectively, confirming the applicability of the Stover–Kincannon model.

Table 2 Performance of the integrated RBC-AS system at different operating conditions

| Run no. | Variable process performance parameters | | | | | | | | | | | | |
	HRT (h)	Influent COD conc. (g/L)	Effluent COD conc. (g/L)	Influent N conc. (g/L)	Effluent N conc. (g/L)	Influent P conc. (g/L)	Effluent P conc. (g/L)	COD removal efficiency (%)	Nitrogen removal efficiency, TN%	Phosphorus removal efficiency, TP%	COD loading rate (g COD/ l d)	Nitrogen loading rate (gN/l d)	Phosphorus Loading rate (gP/l d)
1	9.70	1.185	0.468	0.253	0.117	0.05	0.028	60.47	53.62	43.00	2.86	0.544	0.086
2	9.70	1.151	0.185	0.253	0.112	0.05	0.020	83.93	55.73	58.50	3.86	0.565	0.117
3	9.70	1.135	0.485	0.053	0.019	0.05	0.014	57.26	64.64	71.50	2.60	0.138	0.143
4	9.70	1.201	0.368	0.053	0.018	0.05	0.007	69.33	66.43	85.30	3.33	0.142	0.170
5	9.70	1.018	0.085	0.153	0.029	0.05	0.028	91.65	81.09	43.00	2.48	0.332	0.057
6	18.7	1.352	0.201	0.253	0.073	0.05	0.017	85.07	71.02	64.50	2.30	0.360	0.064
7	18.7	1.352	0.235	0.253	0.076	0.05	0.025	82.61	69.74	49.50	2.23	0.353	0.049
8	18.7	1.318	0.235	0.053	0.016	0.05	0.024	82.17	69.84	52.00	2.16	0.075	0.052
9	18.7	1.318	0.085	0.053	0.007	0.05	0.013	93.55	85.71	74.00	2.46	0.092	0.074
10	14.2	0.952	0.141	0.053	0.023	0.03	0.012	85.18	56.92	57.50	2.16	0.082	0.046
11	14.2	0.952	0.141	0.253	0.056	0.03	0.009	85.184	77.67	70.00	2.16	0.525	0.056
12	14.2	0.952	0.141	0.153	0.025	0.03	0.010	85.18	83.21	65.83	2.16	0.341	0.052
13	14.2	0.952	0.141	0.153	0.028	0.03	0.015	85.18	81.21	49.16	2.16	0.332	0.039
14	14.2	0.985	0.135	0.153	0.083	0.03	0.021	86.29	45.76	27.50	2.26	0.187	0.022
15	14.2	0.985	0.135	0.153	0.082	0.03	0.020	86.29	46.59	32.66	2.26	0.191	0.02
16	14.2	0.985	0.135	0.153	0.082	0.03	0.018	86.29	46.46	37.00	2.26	0.190	0.029
17	14.2	0.985	0.135	0.153	0.080	0.03	0.017	86.29	47.59	43.30	2.26	0.195	0.034
18	14.2	0.985	0.135	0.153	0.073	0.03	0.018	86.29	51.93	39.00	2.26	0.212	0.031
19	14.2	0.985	0.135	0.153	0.070	0.03	0.016	86.29	54.46	43.66	2.26	0.223	0.034
20	14.2	1.318	0.118	0.153	0.031	0.03	0.007	91.02	79.21	76.66	2.39	0.243	0.046
21	9.70	1.035	0.201	0.153	0.090	0.03	0.012	80.51	41.44	57.50	3.33	0.254	0.069
22	9.70	1.318	0.468	0.253	0.106	0.02	0.007	64.47	58.16	65.00	3.39	0.590	0.052
23	9.70	1.168	0.231	0.253	0.097	0.02	0.006	80.22	61.64	69.00	3.74	0.625	0.055
24	9.70	0.915	0.318	0.053	0.022	0.02	0.004	65.20	58.15	79.00	2.38	0.125	0.063
25	9.70	1.168	0.301	0.053	0.022	0.02	0.004	74.16	58.15	79.00	3.46	0.125	0.063
26	9.70	0.985	0.135	0.153	0.023	0.02	0.008	86.29	84.79	58.75	2.26	0.347	0.031
27	18.7	1.368	0.235	0.253	0.086	0.02	0.006	82.82	65.71	67.50	2.26	0.333	0.027
28	18.7	1.301	0.235	0.253	0.046	0.02	0.009	81.91	81.59	52.50	2.13	0.414	0.021
29	18.7	1.301	0.318	0.053	0.017	0.02	0.006	75.53	68.21	68.75	1.96	0.073	0.027
30	18.7	1.368	0.318	0.053	0.018	0.02	0.005	76.73	66.17	76.25	2.09	0.071	0.030

**Table 3** Summary of kinetic constants obtained from the different models applied

Kinetic models	Base for calculation	Kinetic constants	Unit	Values	R^2
Monod	COD	Y	mg/mg	0.712	0.998
		K_s	mg COD/l	55	
		μ_{max}	d^{-1}	5.54	
		k_d	d^{-1}	0.008	
First-order	Nitrogen	k_1	d^{-1}	1.882	0.792
Modified Stover–Kincannon	COD	U_{max}	g COD/l d	15.2	0.813
		K_s	mg COD/l	14.78	
	Nitrogen	U_{max}	g N/l d	10.98	0.96
		K_s	mg N/l	7.11	
	Phosphorus	U_{max}	g P/l d	12.05	0.844
		K_s	mg P/l	6.97	
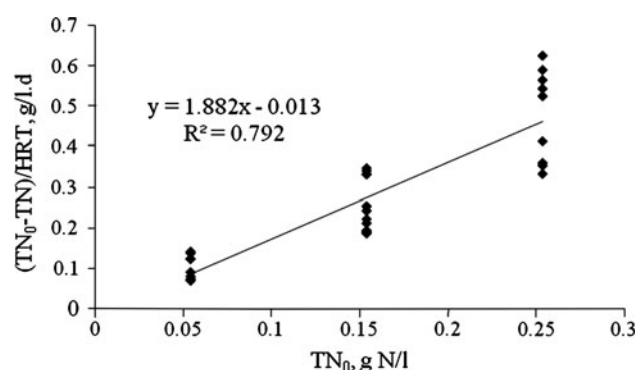
Fig. 3 First-order kinetics model plot for nitrogen removed in the integrated RBC-AS system

A comparative evaluation on the kinetic models

In this study, three kinetic models were applied to carbon and nutrients removal. Table 4 presents the kinetic constants calculated by Monod and Stover–Kincanoon model in different studies. The results demonstrated that generally Y obtained from the present study was larger and the death rate constant was less than the values in literature. This might be due to the higher organic loading rate (OLR), 3.86 g COD/L d, applied in this study in comparison with the others (Borja et al. 2003; Jime'neza et al. 2006; Pa Pala and Bölükba 2005; Isik and Sponza 2005; Pearson et al. 1980; Sponza and Uluko 2008; Pavlostathis and Giraldo 1991; Kaewsuk et al. 2010).

Half-velocity constant is the affinity of microorganisms to the substrate. K_s can be regarded as an indicator of process efficiency; high values of the constant suggest low efficiency of the system. K_s values obtained in this study were less than those obtained in the other studies, while μ_{max} value was larger. From Table 4, there is a decreasing trend in Y as the K_s increases in different studies (Pearson et al. 1980; Pavlostathis and Giraldo 1991; Borja et al.
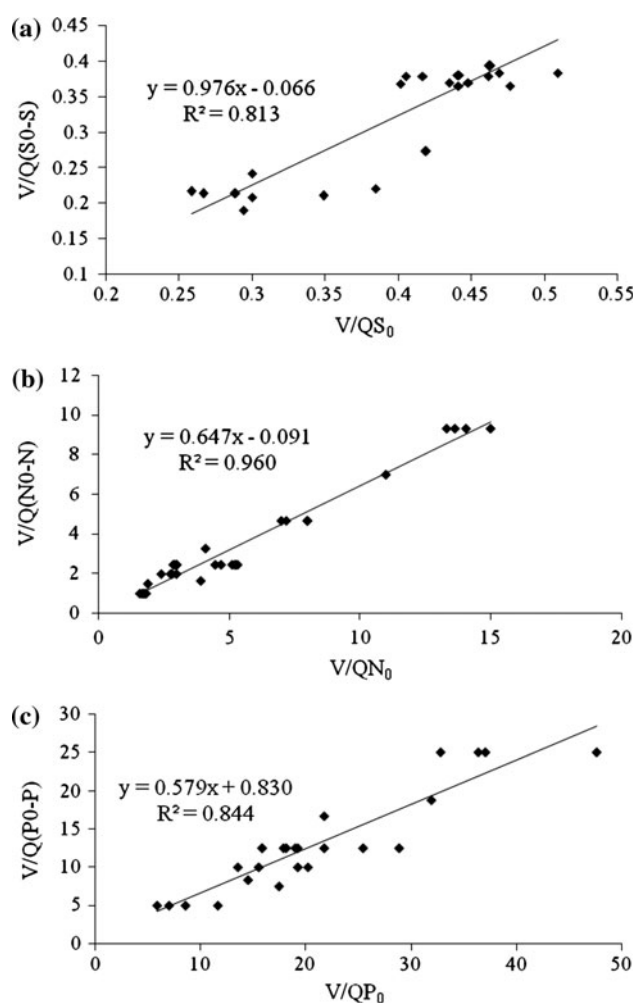
Fig. 4 Stover–Kincannon model plots for **a** COD, **b** nitrogen and **c** phosphorus removal in the integrated RBC-AS system

2003; Isik and Sponza 2005; Pala and Bölükba 2005; Jime'neza et al. 2006; Sponza and Uluko 2008; Kaewsuk et al. 2010).

Table 4 Comparison of kinetic constants in the Monod and Stover–Kincanoon models cited in the literature with the present results for COD removal

| Monod constants | | | | Stover–Kincanoon constants | | | | |
μ_{max} (d^{-1})	K_s (mg COD/l)	Y (mg VSS/mg COD)	K_d (d^{-1})	U_{max} (g COD/l d)	K_S (mg/L)	COD (mg/L)	Base for constant	References
0.3 ± 0.03	–	–	0.34 ± 0.02	–	–	34,000	COD	Borja et al. (2003)
0.14 ± 0.01	–	–	0.14 ± 0.01			81,000	COD	
0.11 ± 0.01	–	–	0.12 ± 0.01			113,100	COD	
0.87 ± 0.03	–	–	0.9 ± 0.04	–	–	23,000	Fermented vinasses	Jime'neza et al. (2006)
0.09 ± 0.02	–	–	0.13 ± 0.09			80,500	Untreated vinasses	
1.13	343	0.7	0.053	–	–	266–800	COD	Jime'neza et al. (2006)
0.8904	8	0.6112	0.0047	–	–	3,600	COD	Pala and Bölükba (2005)
0.5976	1.1	0.7875	0.0025	–	–	3,600	COD	Pala and Bölükba (2005)
0.105	>4,000	0.125	0.0065	7.501	8.211	4,214	Simulated cotton textile wastewater	Pirsaheb et al. (2009)
0.60	12–80	0.38–0.67	0.01–0.14	–	–	–	BOD$_5$	Isik and Sponza (2005)
1.7	43–223	0.31–0.35	0.016–0.068	–	–	–	COD	Isik and Sponza (2005)
0.213	560.29	0.78	0.093	7.502	34.56	3,000	COD	Pearson et al. (1980)
0.84	105–3,180	0.125	0.009	0.77-6.67	8.05		COD	Sponza and Uluko (2008)
1.69	174	0.23	0.14	–	–	1,700–4,000	Dairy wastewater	Pavlostathis and Giraldo-Gomez (1991)
–	–	–	–	83.3	85.5	7,520–11,450	Soybean wastewater	Kaewsuk et al. (2010)
–	–	–	–	83.3	186.23	2,000–15,000	Molasses	Yu et al. (1998)
–	–	–	–	12.148	130.28	1,600–9,100	Poultry slaughterhouse	Büyükkamacı and Filibeli (2002)
5.54	55	0.712	0.008	15.2	14.78	1,100	COD	This study

This conforms the decrease in μ_{max} and increase in endogenous k_d. However, the kinetic constants can be maintained in the appropriate range by adjusting the effective operational and process control factors, SRT and HRT. The results showed that the modified Stover–Kincannon model was more applicable to predict the nitrogen removal efficiency in the RBC-AS system than the first-order model. The low correlation coefficients of the first-order model indicated that this model was not suitable for the reactor with fair degree of precision (Table 3).

From Eq. (12) and Fig. 4b, K_s and U_{max} were computed to be 7.11 g N/L and 10.98 g N/L d, respectively. The Stover–Kincannon model suggests that the substrate removal rate is affected by the organic loading rate entering the reactor as described in Eq. (12). The values of kinetic coefficients (U_{max} and K_s) were lower than those obtained in other studies as seen in Table 4 (Yu et al. 1998; Büyükkamacı and Filibeli 2002; Debik and Coskun 2009).

This could be attributed to the relatively high COD loading rate, as high as 3.86 g COD/L d, applied to the bioreactor in this study. As a result, the maximum substrate utilization rate constant for COD, N and P was obtained as 15.2 COD/L d, 10.98 g N/L d, and 0.625 g P/L d, respectively, suggesting that the reactor possessed an excellent COD, N and P removal capacity.

Conclusion

Kinetic analysis of the RBC-AS system was successfully performed using different kinetic models (Monod, first-order and Stover–Kincannon) with the experimental results obtained in an earlier study (Akhbari et al. 2011). As a result, Monod and Stover–Kincannon models were found to be the appropriate models to describe the bioprocess in the RBC-AS system. According to the Monod model, Y, k_d, μ_{max}, and K_s coefficients were found to be 0.712 g VSS/g COD, 0.008/d, 5.54/d and 55 mg COD/L, respectively. The maximum substrate utilization rate constant for COD, N and P was obtained as 15.2 COD/L d, 10.98 g N/L d, 0.625 g P/L d, respectively, suggesting that the reactor possessed an excellent COD, N and P removal capacity.

The kinetic parameters determined in this study can be used to improve the design and operation of the RBC-AS system on full scale.

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