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Kinetic coefficients for the domestic wastewater treatment using hybrid activated sludge process

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ABSTRACT

In this study, the performance of a novel configuration of the hybrid growth bioreactor in pilot-plant scale (containing of anoxic, aerobic and sedimentation sections) was investigated for Isfahan municipal wastewater treatment plants. The bioreactor performance was evaluated after primary sedimentation tanks under the inlet COD concentration of 0.27 ± 0.02 g/L, at different suspended biomass concentrations of about 3, 4, and 5 as g/L and different total hydraulic retention times 4, 8, and 12 h. An industrial moving bed packing with protected specific surface area of 350 m^2/m^3 was used in the bioreactor with a 30% of filling ratio. The modified Stover–Kincannon and Grau models are applied to predict the bio kinetic coefficients of COD removal. According to the results obtained, the substrate removal rate constant (k_s) for Grau model was in the range of 8.23–10.96 (1/d), and the saturation constant (K_B) value and the maximum total substrate utilization rate (U_{max}) for modified Stover–Kincannon were in the range of 57.4–87.7 (g/L d) and 62.6–91.4 (g/L d), respectively. Also, the results showed that the bioreactor follows the models with 98–99% correlation coefficients.

Keywords: Hybrid growth; Wastewater treatment; Kinetic coefficients; Anoxic; Bioreactor

1. Introduction

The capacity and performance of a wastewater treatment plant (WWTP) is a moving goal, which is very important [1–3]. There is a growing interest for WWTP owners to investigate economical and more efficient techniques rather than conventional wastewater treatment [1–4]. The performance of the wastewater treatment plants can be improved by increasing the biomass concentration in biological systems [5,6]. The biofilm bioreactors have been used for treating of wastewater recently [4–17]. By adding the media, the biomass concentrations and organic loading rate (OLR) can be increased at these bioreactors [10,11]. The micro-organisms/activated sludge grows on the internal surface of the media. The micro-organisms consume the organic matter from the wastewater. The aeration system keeps the carriers with activated sludge in motion. The hybrid activated sludge reactor is more efficient compared with the suspended growth processes for wastewater treatment [12–14]. These processes have high performance and stability because of their capacity of keeping high sludge retention time (SRT) even when operating at low hydraulic retention time (HRT). Also

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the treatment plant requires less space and HRT can be relatively low [14–17].

The biological treatment processes can be designed based on the parameters such as OLR, HRT, SRT, the food per micro-organism ratio (F/M), and biological kinetic models [18]. The biological models are used for the prediction of result of various inputs [18,19]. Also these models are used to determine system performance and optimal operating conditions [19]. There are various models for aerobic treatment, depending on the type of wastewater [18,19]. Each kinetic model is only suitable for specific cases and processes [19]. These models which are applied for the hybrid growth systems include the first-order, the Grou (second-order), and modified Stover–Kincannon models [18]. The aim of this study was the determination of the kinetic coefficients of COD removal through the Grou and the modified Stover–Kincannon models. Another aim of this study was to introduce a novel hybrid growth system with a simple design and a high efficiency in the removal of contaminants that is a modern method to design WWTP.

2. Materials and methods

2.1. Wastewater

The influent of bioreactor is pumped from south Isfahan WWTP settling basin in to the designed bioreactor inlet. The wastewater specifications after primary settling tank are presented in Table 1. The south Isfahan WWTP activated sludge is used for the bioreactor launching.

2.2. Bioreactor

A pilot plant fabricated from carbon steel 37 is used in this study. It has a rectangular shape, external dimensions of 150 cm length, 100 cm width, and a height of 150 cm. The effective height of the unit is 140 cm, incorporating a reactor total volume of 2,100 L. The clarifier position is adjusted at the end of the system, after the aeration section is filled with lamella plates. Aeration section is performed by a small bubble diffuser that is located on the bioreactor bottom. An air line is employed at the clarifier bottom to create an airlift system for sludge recycling and excess sludge disposal. The novel hybrid bioreactor apparatus is shown schematically in Fig. 1.

Table 1
Characteristics of the raw wastewater

Parameter	Value
COD (g/L)	0.27 ± 0.02
BOD_5 (g/L)	0.11 ± 0.01
pH	7.2–7.7
TSS (g/L)	0.13 ± 0.015
VSS/TSS	0.79

The industrial media is used in the pilot. The media chosen for this investigation is made of polyethylene. The technical media specifications are summarized in Table 2. The media with a filling reactor volume ratio of 30% is utilized in the anoxic and aeration sections. The protected surface area is 350 m^2/m^3 and total surface area is 480 m^2/m^3. The protected surface area is considered for design purposes.

2.3. Experimental procedure

The anoxic and the aeration sections dissolved oxygen are maintained less than 0.5 and between 3.6 and 5.1 mg/L, respectively. The pilot is placed in WWTP outdoors at ambient temperature without any insulation. The temperature, dissolved oxygen, and pH are daily measured at different times. The amount of COD removal efficiency is measured in a continuous flow of wastewater stream at the suspended biomass concentrations of about 3, 4, and 5 g/L and in three different HRT's of 4, 8, and 12 h, respectively. The media are placed in a different tank for biofilm formation. The media are inserted to the anoxic and aeration sections after about 40 d. Then the bioreactor performance was studied after compatibility of micro-organisms, biofilm formation on the media, and adjusting the suspended biomass concentration of about 3 g/L. Due to slight changes in the attached biomass concentration after the biofilm formation, performance of bioreactor was studied by changing the suspended biomass concentration at three levels. Attached biomass concentration was in the range of 3.15–3.6 g/L. This way, the performance of the bioreactor was examined by COD concentration of 0.27 ± 0.02 g/L at biomass concentration of about 6 g/L (suspended biomass concentration at about 3 g/L) at three levels of HRT of 6, 9, and 12 h. Sampling is performed after achieving steady-state condition. The sampling is carried out at the influent and effluent wastewater from the bioreactor. All the determinations are conducted according to the standard methods for the examination of water and wastewater [20].

The performance of the system is evaluated in terms of total COD removal. The flow of wastewater is regulated proceeding from the mentioned total HRT. The suspended biomass concentration is regulated by the airlift system at the desired range. The gravimetric method is applied to measure the attached biomass concentration. The quantitative determination of the attached biomass involves discharging 10–20 numbers

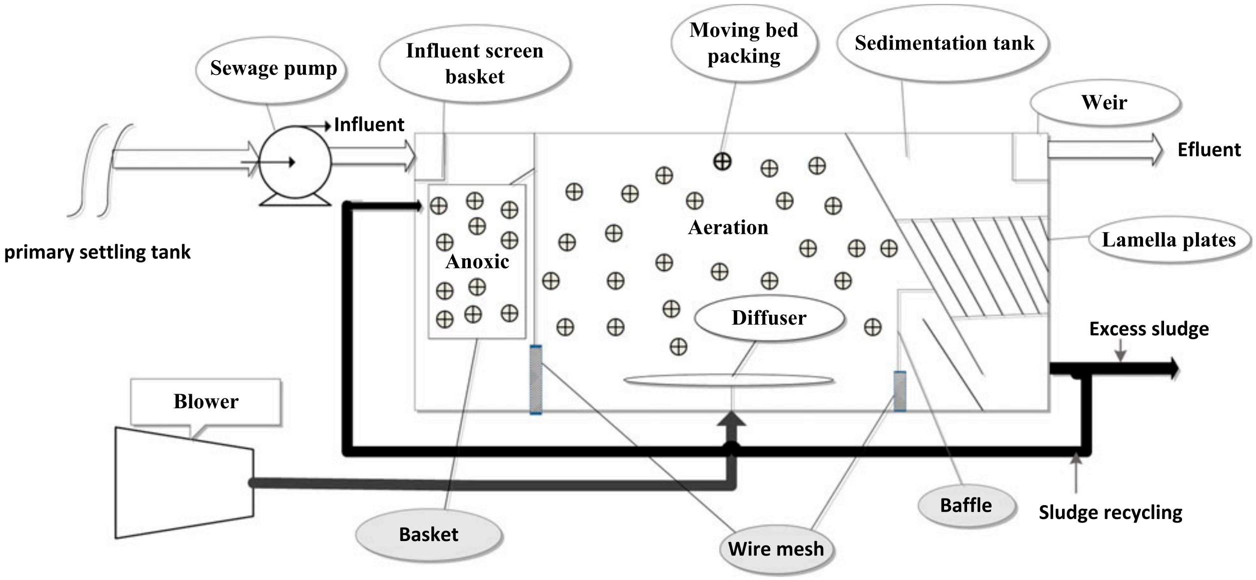

Fig. 1. Schematic view of the novel hybrid system applied in this study.

Table 2
The media specifications

Technical specifications	Industrial media
Material	Polyethylene
Specific surface area (protected)	350 m^2/m^3
Maximum fill	30%
Density	920–970 kg/m^3
Number of units per m^3	160
Average weight per media	0.5437 g
Color	Natural white

of media, drying over 1 h at 105˚C, and finally weighing the media and determining the difference weight of used and unused media. The attached biomass concentration is calculated by multiplying the weight difference and the media bulk number density [21,22].

2.4. The Grou model

The general equation of a second-order substrate removal kinetic model is given [23]:

$$\frac{dS}{dt} = k_s \cdot X \cdot \left(\frac{S_e}{S_i}\right)^2 \tag{1}$$

Integration and linearilization of Eq. (1) result the following:

$$\frac{S_i \cdot \text{HRT}}{S_i - S_e} = \text{HRT} + \frac{S_i}{k_s \cdot X} \tag{2}$$

The second term of the right part of this equation is assumed as a constant, therefore:

$$\frac{S_i \cdot \text{HRT}}{S_i - S_e} = n \cdot \text{HRT} + m \tag{3}$$

where $m = \frac{S_i}{k_s X}$ and n is a constant. The $\frac{S_i}{S_i - S_e}$ expresses the substrate removal efficiency and is symbolized as $1/E{\cdot}X$ is the average biomass concentration in the reactor (mg/L), and k_s is the second-order substrate removal rate constant (1/d). Therefore, Eq. (3) can be written as follows:

$$\frac{\text{HRT}}{E} = n \cdot \text{HRT} + m \tag{4}$$

The values of m and n are calculated from the intercept and slope of the straight lines on the figures, respectively.

2.5. The modified Stover–Kincannon model

The original Stover–Kincannon model was carried out on a rotating biological contactor (RBC) [24]:

$$\frac{dS}{dt} = \frac{Q}{V}(S_i - S_e) = \frac{U_{max}\left(\frac{QS_i}{A}\right)}{K_B + \left(\frac{QS_i}{A}\right)} \tag{5}$$

where dS/dt is the substrate removal rate (g/L d); Q is the flow rate (L/d), V is the reactor liquid volume (L), and S_0 and S_e are the influent and effluent substrate concentrations (g/L), respectively. A denotes the total disc surface area on which there is immobilized biomass concentration. The U_{max} represents the maximum removal rate of substrate (g/L d) and K_B is the constant of saturation value (g/L d). In this model for RBC rotating biodiscs, the suspended solid is neglected due to the addition of biomass within the biofilm surface area considered for the definition of biomass. On the other hand, the biomass concentration is expressed by the volume in the modified model [25,26]. However, the effective volume of the reactor is used in this version of the Stover–Kincannon model due to the difficulties in measuring the active surface area which supports the biofilm growth. The substrate consumption rate is explained as a function of the volumetric-loaded organic in the modified Stover–Kincannon model [27]. The modified Stover–Kincannon model is given by:

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \frac{Q}{V}(S_i - S_e) = \frac{U_{max}\left(\frac{QS_i}{V}\right)}{K_B + \left(\frac{QS_i}{V}\right)} \tag{6}$$

The following equation is obtained by inverting Eq. (6):

$$\left(\frac{\mathrm{d}S}{\mathrm{d}t}\right)^{-1} = \frac{V}{Q(S_i - S_e)} = \frac{K_B}{U_{max}}\left(\frac{V}{QS_i}\right) + \frac{1}{U_{max}} \tag{7}$$

3. Results and discussion

The measurement conditions and the COD removal efficiencies' results for each run are presented in Table 3. The system has a more favorable efficiency about 96% at the suspended biomass concentration of 4.928 ± 0.174 g/L and attached growth of 2.766 ± 0.238 g/L, at HRT of 4 h. The results show that a decrease in the OLR leads to reduce in the system efficiency. An increase in the biomass concentration increases the system efficiency.

The COD removal efficiency and OLR is increased by media addition, while the HRT is decreased; hence, decreased the tank's volume and costs.

3.1. Kinetic modeling

3.1.1. The Grau model

Fig. 2(a)–(c) shows the effect of the total biomass concentration on the kinetic coefficients of the Grau model. In order to determine the kinetic coefficients (m, n, and k_s) Eq. (4) is plotted in Fig. 2. The values of m and n are, respectively, found to be 0.0055 and 1.1064 with correlation coefficients of (R^2) 0.9814. The substrate removal rate constant (k_s) is calculated from the equation $m = S_0/(k_s X)$ as 8.2367 (1/d) for the suspended biomass concentration of 3.066 ± 0.096 g/L and the attached biomass concentration of 2.894 ± 0.162 g/L. The substrate removal depends on the second-order substrate removal rate constant (k_s) which is related to the unit of micro-organism. The removal rate constants are 9.9675 and 10.9663 (1/d) for the suspended biomass concentration of 4.092 ± 0.112 and 4.928 ± 0.174 as g/L, respectively. The results indicated that with increasing the biomass concentration, the k_s increased. In this case, increasing efficiency was due to the increasing population of micro-organisms in the biological systems, which by increasing these organic materials was consumed faster by micro-organisms, and thus enhance the substrate removal rate constant (k_s).

3.1.2. The modified Stover–Kincannon model

Fig. 3(a)–(c) shows the effect of the total biomass concentration on the kinetic coefficients of the modified Stover–Kincannon model. The values of K_B/U_{max} and $1/U_{max}$ are obtained from the slope of the line by plotting V/QS_i vs. $V/Q(S_i - S_e)$ in Eq. (7). The plots the reciprocal of total substrate removal rate, $V/Q(S_0 - S_e)$, against the reciprocal of $V/(QS_0)$ are shown is Fig. 3(a)–(c) for the suspended biomass concentrations of 3.066 ± 0.96, 4.092 ± 0.112, and 4.928 ± 0.174 as g/L and the attached biomass concentration of (2.485–3.056) g/L.

The saturation constant (K_B) value and the maximum total substrate utilization rate (U_{max}) are calculated and are presented in Table 4. The experimental results with high correlation coefficient were applied to the model.

The K_B and U_{max} values obtained in Figs. 3(a)–(c) can be used to determine the volume required to decrease the influent organic concentration from S_i to S_e or to determine the effluent substrate concentration for a given V and S_i. Substituting Eq. (7) into Eq. (6), results in:

$$QS_i = QS_e + \left(\frac{U_{max}\left(\frac{QS_i}{V}\right)}{K_B + \left(\frac{QS_i}{V}\right)}\right)V \tag{8}$$

This equation can then be solved for either the volume of the biological system in the bioreactor or the effluent substrate concentration. Thus,

$$V = \frac{QS_i}{\left(\frac{U_{max}S_i}{S_i - S_e}\right) - K_B} \tag{9}$$

Table 3
The investigated parameters in steady-state for the novel hybrid bioreactor at steady-state condition

COD (g/L)	Biomass concentration (g/L)		HRT (min)				OLR (g COD/L d)	SRT (d)	F/M (g COD/g MLSS d)	Efficiencies (%)
	Suspended	Attached	Anoxic (min)	Aerobic (min)	Clarifier (min)	Total (min)				
0.27 ± 0.02	3.066 ± 0.096	2.894 ± 0.162	270	450	270	720	0.54	27.3	0.09	90.8
			90	300	90	480	0.81	17.2	0.14	92.1
			45	150	45	240	1.62	8.78	0.28	93.1
	4.092 ± 0.112	2.68 ± 0.195	270	450	270	720	0.54	29.9	0.08	91.2
			90	300	90	480	0.81	20.1	0.12	93.3
			45	150	45	240	1.62	9.34	0.24	94.2
	4.928 ± 0.174	2.766 ± 0.238	270	450	270	720	0.54	34.2	0.07	92.7
			90	300	90	480	0.81	22.6	0.10	94.6
			45	150	45	240	1.62	11.3	0.21	96.3

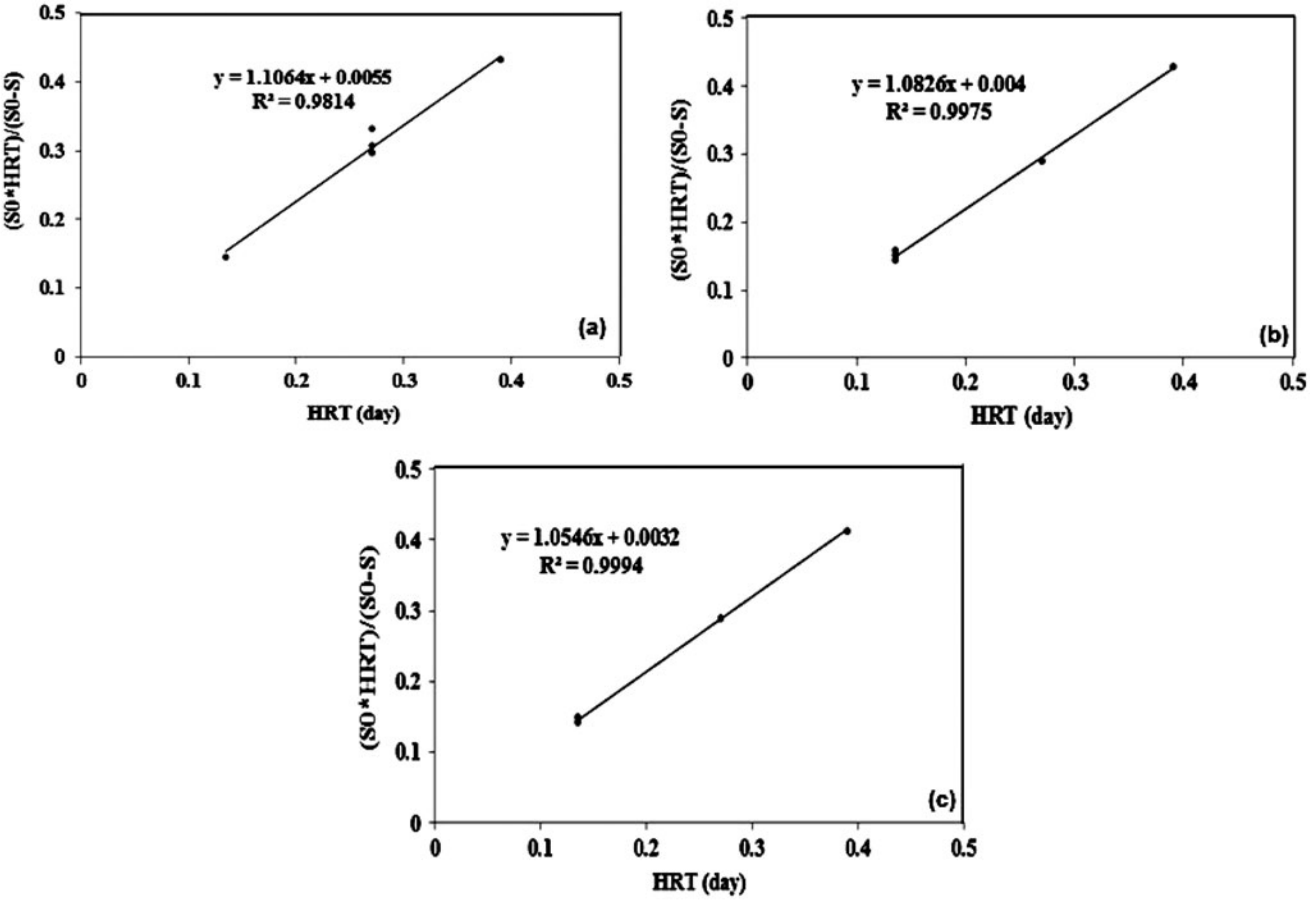

Fig. 2. The Grou model plot at biomass concentrations of: (a) 5.96 ± 0.258 g/L, (b) 6.772 ± 0.307 g/L, and (c) 7.694 ± 0.412 g/L.

$$S_e = S_i - \left(\frac{U_{max} S_i}{K_B + \left(\frac{QS_i}{V}\right)}\right) V \tag{10}$$

V and S_i are obtained by substituting K_B and U_{max} from Table 4 in Eq. (9) and (10) for biomass concentrations of 5.96 ± 0.258, 6.772 ± 0.307, and 7.694 ± 0.412 g/L. The results showed that with increasing the biomass

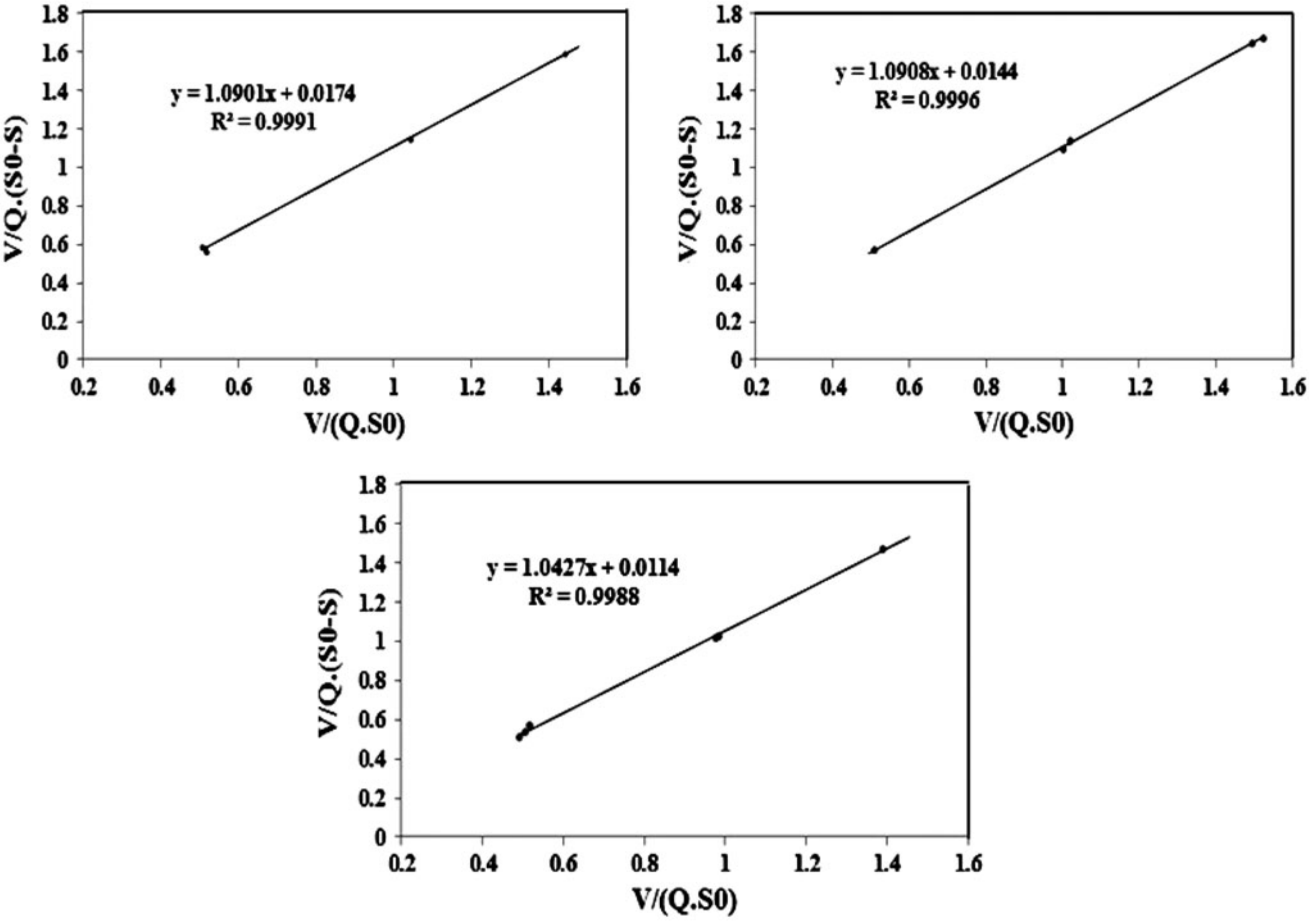

Fig. 3. The modified Stover–Kincannon plot at biomass concentrations of: (a) 5.96 ± 0.258 g/L, (b) 6.772 ± 0.307 g/L, and (c) 7.694 ± 0.412 g/L.

Table 4
The Grau and Stover–Kincannonmodels kinetic coefficients for a hybrid growth novel bioreactor at different MLSS concentrations

		Grau second-order				Stover–Kincannon		
Substrate	Biomass concentration (mg/L)	*n*	*m*	K_s (1/d)	R^2	U_{max} (g/L d)	K_B (g/L d)	R^2
Domestic (COD)	5.96 ± 0.25	1.11	0.005	8.24	0.98	57.47	62.65	0.99
	6.77 ± 0.30	1.08	0.004	9.97	0.99	69.44	75.75	0.99
	7.69 ± 0.41	1.05	0.003	10.97	0.99	87.72	91.47	0.99

concentration, the K_B and U_{max} increase due to increasing in population of micro-organisms in the biological systems. Thus, the organic materials are consumed faster by micro-organisms, and the K_B and U_{max} increase.

Previous studies are obtained in different pollutant concentrations and the constant biomass concentration. In this study, kinetic coefficients are obtained for the constant COD concentration, and the effect of biomass concentration is investigated on the kinetic coefficients. The constants determined from the applied models in the previous studies are listed in Table 5 and compared with coefficients obtained here. The K_s values are larger than those reported in the literature. The difference may be explained by the fewer

Table 5
Comparison of kinetic coefficients in the Stover–Kincannon and the Grau models cited in the literature with the present results

Models	Substrate	S_0 (g/L)	HRT (d)	Kinetic parameters			References
				U_{max}	K_B		
Stover–Kincannon	Soybean	7.52–11.45	1.0–1.45	83.3	85.5		[28]
Stover–Kincannon	Simulated	0.75–4.5	1.0	8.3	9.45		[29]
Stover–Kincannon	Simulated	0.75–2.25	0.5–1.0	101.0	106.8		[30]
Stover–Kincannon	Municipal	0.27 ± 0.02	0.135–0.33	57.4–87.7	62.6–91.4		This study
				K_s	m	N	
Grau second-order	Municipal	0.23–0.445	0.25–1.0	0.217	0.002	1.346	[24]
Grau second-order	Molasses	2–15	0.5–2.0	10.81	0.033	1.192	[25]
Grau second-order	Simulated	0.75–4.5	1.0	0.337	0.562	1.095	[29]
Grau second-order	Simulated	0.75–2.25	0.5–1.0	3.582	0.047	1.007	[30]
Grau second-order	Municipal	0.27 ± 0.02	0.135–0.33	8.2–10.9	0.0032–0.0055	1.0546–1.1064	This study

rates of the utilized substrate and applying a real wastewater. The real wastewater is a very important factor, because the suspended solids and inhibitors are effective on the kinetic coefficients. The organic matters such as phenol, furfural and hydrocarbon, and heavy metals compounds like lead, nickel, and chromium ions as inhibitors are toxic for the microorganisms in the real wastewater. According to the Stover–Kincannon kinetic model, the saturation constant K_B and the U_{max} values obtained in this study are between the determined values range reported in other studies.

4. Conclusion

The results indicated that the hybrid activated sludge bioreactor which was investigated in this study is capable to biodegrade the organic matter higher than 96%. The results showed that the bioreactor have highest efficiencies at different biomass concentrations with OLR 1.62 g COD/L d. The results showed by increasing the biomass concentration in the biological systems, the COD removal efficiency and bio kinetic coefficients are increased. It is revealed that the modified Stover–Kincannon and the Grau models are highly correlated with the experimental results for the bio kinetic modeling of the hybrid growth bioreactor.

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Symbols

S_i — influent substrate concentration (mg/L)
S_e — effluent substrate concentration (mg/L)
X — biomass concentration (mg/L)
HRT — hydraulic retention time (d)
K_s — the second-order substrate removal rate constant (1/d)
n — constant
m — constant
E — the substrate removal efficiency (%)
Q — flow rate (L/d)
V — the reactor liquid volume (L)
A — total disc surface area (m^2)
U_{max} — the maximum removal rate of substrate (g/L d)
K_B — the constant of saturation value (g/L d)

References

[1] J. Daw, K. Hallett, J. DeWolfe, I. Venner, Energy efficiency strategies for municipal wastewater treatment facilities, Contract 303 (2012) 275–3000.

[2] M.M. Hamed, M.G. Khalafallah, E.A. Hassanien, Prediction of wastewater treatment plant performance using artificial neural networks, Environ. Model. Softw. 19 (2004) 919–928.

[3] A. Gallego, A. Hospido, M.T. Moreira, G. Feijoo, Environmental performance of wastewater treatment plants for small populations, Resour. Conserv. Recycl. 52 (2008) 931–940.

[4] S.C. Oliveira, M. Von Sperling, Performance evaluation of different wastewater treatment technologies operating in a developing country, J. Water Sanit. Hyg. Dev. 1 (2011) 37–56.

[5] J. Chung, W. Bae, Y.W. Lee, B.E. Rittmann, Shortcut biological nitrogen removal in hybrid biofilm/suspended growth reactors, Process Biochem. 42 (2007) 320–328.

[6] W. Jianlong, S. Hanchang, Q. Yi, Wastewater treatment in a hybrid biological reactor (HBR): Effect of organic loading rates, Proc. Biochem. 36 (2000) 297–303.

[7] F. Yang, Y. Wang, A. Bick, J. Gilron, A. Brenner, L. Gillerman, G. Oron, Performance of different configurations of hybrid growth membrane bioreactor (HG-MBR) for treatment of mixed wastewater, Desalination 284 (2012) 261–268.

[8] J.H. Seok, S.J. Komisar, Comparison of suspended growth and hybrid systems for nitrogen removal in ammonium bisulfite pulp mill wastewater, Environ. Technol. 24 (2003) 31–42.

[9] C. Nicolella, M.C.M. Van Loosdrecht, J.J. Heijnen, Wastewater treatment with particulate biofilm reactors, J. Biotechnol. 80 (2000) 1–33.

[10] H.S. Lee, S.J. Park, T.I. Yoon, Wastewater treatment in a hybrid biological reactor using powdered minerals: Effects of organic loading rates on COD removal and nitrification, Proc. Biochem. 38 (2002) 81–88.

[11] B. Rusten, B. Eikebrokk, Y. Ulgenes, E. Lygren, Design and operations of the Kaldnes moving bed biofilm reactors, Aquac. Eng. 34 (2006) 322–331.

[12] M. Tizghadam, Ch Dagot, M. Baudu, Wastewater treatment in a hybrid activated sludge baffled reactor, Hazard. Mater. 154 (2008) 550–557.

[13] S. Vendramel, M. Dezotti, G.L. Sant'Anna, Nitrification of an industrial wastewater in a moving-bed biofilm reactor: Effect of salt concentration, Environ. Technol. 32 (2011) 837–846.

[14] H. Odegard, B. Rusten, T. Westrum, A new moving bed biofilm reactor—Application and results, Water Sci. Technol. 29 (1994) 157–165.

[15] A. Aygun, B. Nas, A. Berktay, Influence of high organic loading rates on COD removal and sludge production in moving bed biofilm reactor, Environ. Eng. Sci. 25 (2008) 1311–1316.

[16] R. Salvetti, A. Azzellino, R. Canziani, L. Bonomo, Effects of temperature on tertiary nitrification in moving-bed biofilm reactors, Water Res. 40 (2006) 2981–2993.

[17] M. Rodgers, X.M. Zhan, B. Gallagher, A pilot plant study using a vertically moving biofilm process to treat municipal wastewater, Bioresour. Technol. 89 (2003) 139–143.

[18] F.J. Beltran, J.F. Garcia-Araya, P.M. Alvarez, Estimation of biological kinetic parameters from a continuous integrated ozonation-activated sludge system treating domestic wastewater, Biotechnol. Prog. 16 (2000) 1018–1024.

[19] L. Metcalf, H.P. Eddy, G. Tchobanoglous, Wastewater Engineering: Treatment, Disposal, and Reuse, McGraw-Hill, New York, NY, 2005.

[20] Standard Methods for the Examination of Water and Wastewater, twentieth ed. American Public Health Association, American Water Works Association, Water Environment Federation, Washington, DC, 1998.

[21] H. Aspegren, U. Nyberg, B. Andersson, S. Gotthardsson, J.L.C. Jansen, Post denitrification in a moving bed biofilm reactor process, Water Sci. Technol. 38 (1998) 31–38.

[22] S. Luostarinen, S. Luste, J. Rintala, Nitrogen removal from on-site treated anaerobic effluents using intermittently aerated moving bed biofilm reactors at low temperatures, Water Res. 40 (2006) 1607–1615.

[23] F. Carta-Escobar, J. Pereda-Marin, P. Alvarez-Mateos, F. Romero-Guzman, M.M. Duran Barrantes, Aerobic purification of dairy wastewater in continuous regime part II: Kinetic study of the organic matter removal in two reactor configurations, Biochem. Eng. J. 22 (2005) 117–124.

[24] P. Grau, M. Dohanyas, J. Chudoba, Kinetic of multicomponent substrate removal by activated sludge, Water Res. 9 (1975) 637–642.

[25] E.L. Stover, D.F. Kincannon, Rotating biological contactor scale up and design, Proceedings of the First International Conference on Fixed Film Biological Processes, Kings Island, Ohio, 1982.

[26] A. Broch-Due, R. Andersen, O. Kristoffersen, Pilot plant experience with an aerobic moving bed biofilm reactor for treatment of NSSC wastewater, Water Sci. Technol. 29 (1994) 283–294.

[27] J.R. Flora, M.T. Suidan, P. Biswas, G.D. Sayles, A modeling study of anaerobic biofilm systems: I. Detailed biofilm modeling, Biotechnol. Bioeng. 46 (1995) 43–53.

[28] H. Yu, F. Wilson, J.H. Tay, Kinetic analysis of an aerobic filter treating soybean wastewater, Water Res. 32 (1998) 3341–3352.

[29] S.M. Borghei, S.H. Hosseiny, Modeling of organic removal in a moving bed biofilm reactor (MBBR), ScienticaIranica 9 (2002) 53–58.

[30] S.M. Borghei, M. Sharbatmaleki, P. Pourrezaie, G. Borghei, Kinetics of organic removal in fixed-bed aerobic biological reactor, Bioresour. Technol. 99 (2008) 1118–1124.