DETERMINATION OF BIOKINETIC COEFFICIENTS FOR ACTIVATED SLUDGE PROCESSES ON MUNICIPAL WASTEWATER

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ABSTRACT

Biokinetic coefficients and efficiency for three activated sludge processes including conventional, extended aeration, and contact stabilization were determined in pilot-scale for six months in Isfahan south municipal wastewater treatment plant. These systems were operated under two different MLSS concentrations in aeration tank. For each MLSS, five periods were considered in base of flow rate and sludge retention time (SRT). The samples from the influent wastewater, reactor and effluent were collected periodically and experimented by the Standard Methods. The data were analyzed by the Excel and SPSS softwares. The investigation showed that the yield coefficient (Y), decay coefficient (kd), maximum specific growth rate and saturation constant (K_s) for conventional activated sludge process were in the range of 0.48-0.8 mgVSS/mg sCOD, 0.0189-0.026 1/day, 0.95-0.98 1/day and 52-71 mg sCOD/L, extended aeration: 0.6174-1.2512 mgVSS/mg sCOD0.0198-0.0309، 1/day 1.96-3.17 ، 1/day and 311.7-508 mg sCOD/L and for contact stabilization: 0.6322-0.713 mgVSS/mg sCOD1 0.0172-0.0387 ،/d0.23-1 0.42/d and13.8-50.8 mg sCOD/L, respectively. In the conventional and contact stabilization processes values of the coefficients were within the range of those reported in the literature. However, in the extended aeration process, values of K_s and Y in MLSS of 5000mg/L were out of ranges. The sensitivity analysis of changes in the biokinetic coefficients showed direct relationship of kd and Ks with the concentration of the effluent substrate. Whereas μ_{max} is inversely related to concentration of the effluent substrate. In addition, regardless of the type of substrate and MLSS concentration, the effluent substrate concentration is more sensitive to μ_{max} than kd and Ks. The results also showed a COD removal efficiency ranging for conventional process between 83 and 92.5%, for extended aeration process between 88 and 93.8%, and for contact stabilization process 77 and 92%. The effluent COD was simulated using the biokinetic coefficients determined during the study.

Key words: Wastewater treatment; Biokinetic coefficient; Activated sludge process; Monod equation

INTRODUCTION

In the past, designs of biological wastewater treatment processes were based on the empirical parameters developed by experience, which included hydraulic loading, organic loading and retention time. Nowadays, the design utilizes empirical as well as rational parameters based on biological kinetic equations. Theses equations describe growth of biological solids, substrate utilization rates, food-to-microorganisms ratio, and the mean cell residence time. Reactor volume, substrate utilization, biomass growth, and the effluent quality can be calculated from those equations (Qasim, 1999).

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Biokinetic coefficients used in the design of activated sludge processes include specific growth rate(μ), maximum rate of substrate utilization per unit mass of microorganisms (k: 2-10 1/day), half velocity constant (K_s: 10-60 mg COD/L), maximum cell yield (Y: 0.3-0.6 mgVSS/mg COD), and endogenous decay coefficient (kd: 0.06-0.15 1/day)(Metcalf and Eddy, 2003).

In the different wastewater treatment processes, biokinetic coefficients have been evaluated by several investigators (Henze, 1992; San, 1992; Karin Kovarova-Kovar, 1998). Muhammad Al-Malack determined biokinetic coefficients of an immersed membrane bioreactor for municipal wastewater treatment. Biokinetic coefficients determined under different MLSS concentrations and organic loading rates (Al-Malack, 2006).

Naghizadeh determined biokinetic parameters in municipal wastewater treatment with a submerged membrane reactor by the monod equation. The results showed that Y, kd, Ks and μ_{max} coefficients were 0.67 mgVSS/mgCOD, 0.5 1/day, 65.5 mg/L and 1.86 1/day, respectively (Naghizadeh, 2008). Eleni Vaiopoulou studied kinetics of nitrification, denitrification and dephosphatation in the aerobic, anoxic and anaerobic stages of a pilot scale biological nutrient removal plant treating municipal wastewater. The results showed that the nitrification process follows Monod type kinetics (Eleni Vaiopoulou and Alexander Aivasidis, 2007).

Talaie Khozani studied the determination of biokinetic coefficients of crude oil biodegradation using *Pseudomonas aeruginosa* bacteria. The biokinetic coefficients based on modified Monod equation were calculated. The results showed that kd, Y, k and Ks were equal 0.107 1/day, 0.882 mg/L, 9.39 1/day and 169.3 mg/L, respectively (Talaie *et al*., 2010). Pala and Bolukbas evaluated the kinetic parameters for biological CNP removal from a municipal wastewater through batch tests (Pala and Bolukbas, 2005). Yenkie *et al* determined biokinetics of wastewater treatment in the high performance compact reactor (HCR) using different cell residence times (Yenkie *et al.*, 1992). Joseph and Malina determined biokinetic coefficients for hydraulic retention time of 24 h in high-rate biological treatment of wastewater at the Pantex facility (alternative to the existing aerated lagoon-pond system), (Joseph and Malina, 1999).

Basic equations that describe the interaction between the growth of microorganisms and utilization of the growth limiting substrate in activated sludge processes are based on Monod model, which is considered as the most commonly and widely used for determining the biokinetic coefficients.

In continuous-flow and completely-mixed reactor, determination of the biokinetic coefficients is usually achieved by collecting data from lab-scale or pilot-scale experimental setups operated at various hydraulic retention times (HRTs) and/or at various sludge retention times (SRTs) (Metcalf and Eddy, 2003).

The main objective of this study was the determination of kinetic parameters Y, k_d, μ_{max} and K_s for activated sludge processes through three types including: conventional, extended aeration and contact stabilization activated sludge systems on municipal wastewater in pilot-scale. The practical objective was also the efficiency evaluation of one of the big Isfahan wastewater , WWTP, treatment plants (Isfahan South WWTP) with conventional activated sludge process, which provides services for about 1 million persons.

MATERIALS AND METHODS

Description of the systems setup

Fig.1 shows the diagram of activated sludge processes (conventional, extended aeration and contact stabilization) in pilot-scale used in this study. Each activated sludge system in pilot-scale included aeration tank, secondary sedimentation tank and auxilary apparatus. The effective volume of each reactor in the conventional and extended aeration activated sludge processes was 300 L, whereas effective volume of contact basin and stabilization basin in contact stabilization process was 54 L and 238 L, respectively. Influent wastewater to extended aeration and contact stabilization systems was raw wastewater that was passed of screen and grit chamber, but influent wastewater to conventional system was the effluent wastewater of primary sedimentation tank. For providing and maintaining aerobic conditions in the reactor, stone air diffusers were fixed in the bottom of basins. The operation of pilot plant was programmed to switch on and off by Programming Logic Control.

A steady-state condition was assumed to be reached when fairly constant biomass growth and permeate COD were attained. During the

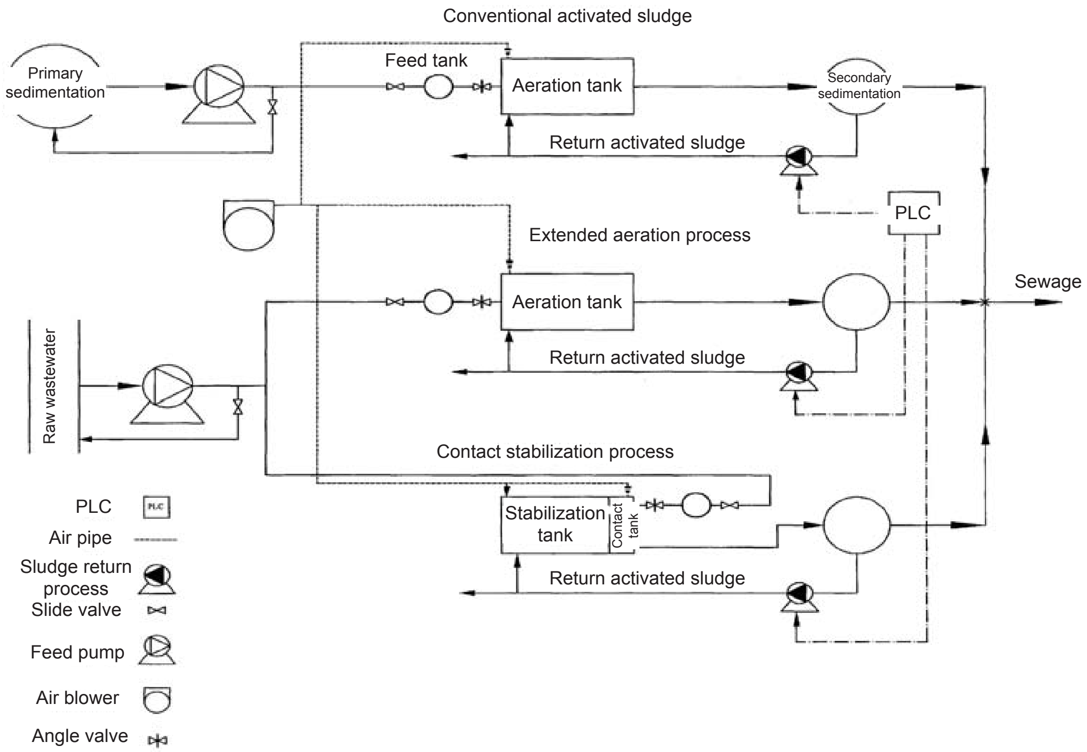

Fig.1: Schematic diagram of three activated sludge processes used in this study

first stage of the investigation, the mixed liquor suspended solids concentration, in the aeration tank was kept constant. The first steady-state condition was achieved after 25 days from the start of the unit operation. The steady-state condition for each SRT during first stage in each process was maintained for about 10 days, and during the second stage, the steady-state condition in each process was maintained for about 5 days.

Wastewater characteristics
Raw and effluent wastewaters of the primary sedimentation tank from Isfahan South WWTP were used for feeding the reactors in pilot plants. The general characteristics of the raw wastewater used in the study are shown in Table 1.

Table 1: Characteristics of the raw wastewater

Parameter	Value (mg/L)
BOD_5	240
COD	575
$sBOD_{ave}$	85.3
$sCOD_{ave}$	180.25
TSS_{in}	226
pH_{in}	7.64
sBOD/sCOD	0.47
VSS/TSS	0.81

Analytical methods
Samples from the influent wastewater, reactor and effluent were analyzed for various physical and chemical parameters in accordance with the Standard Methods (APHA, 2005). The TSS, VSS and sCOD parameters were experimented in influent and effluent wastewater every day but BOD_5, $sBOD_5$ and COD parameters were tested 3 times per week. Also temperature in the bioreactors was held about 20 °C and DO (dissolve oxygen) was 2 mg/L in the biological reactors. After sampling, the data were analyzed by Excel and SPSS softwares.

Experimental procedure
Initial seeding of each bioreactor (conventional and extended aeration) was accomplished by inoculating the bio-reactor with 100 L, in contact stabilization process: the contact basin with 54 L and the stabilization basin with 70 L of returned activated sludge, respectively. During the first 25 days of operation, the biomass was allowed to acclimatize to the influent substrate.
The investigation was carried out at different MLSS concentrations in each process, as:
-Conventional process (2000 and 3000 mg/L

-Extended aeration process (4000 and 5000 mg/L)
-Contact stabilization process (2000 and 3000 mg/L)
Each MLSS value was subjected to five different sludge retention times (SRT). Sludge was withdrawn from the sedimentation tank once a day to keep the SRT at the designated values. Biokinetic coefficients were determined by collecting data from pilot-scale experiments and under equations. MLSS concentration was assumed steady in each process and section; then flowrate and SRT process computation were changed, but the tank volume was constant in each process.

$$\frac{1}{SRT} = Y\,U - K_d = Y\,\frac{S_0 - S}{\theta X} - K_d \qquad (1)$$

$$\frac{\theta X}{S_0 - S} = \frac{K_s}{K}\,\frac{1}{S} + \frac{1}{K} = \frac{1}{U} \qquad (2)$$

where:
SRT: Solids retention time, d
Y: Biomass yield, mg VSS/mg sCOD
U: Substrate utilization rate, mg sCOD/mg VSS.d
kd:Endogenous decay coefficient, 1/d
S0:Influent substrate concentration, mg sCOD/L
S: Effluent substrate concentration, mg sCOD/L
X: Biomass concentration, mg VSS/L
ϴ: Hydraulic retention time, d
Ks: Half-velocity constant, mg sCOD/L
k: Maximum rate of substrate utilization, mg sCOD/mg VSS.d

RESULTS

Conventional activated sludge process

During the first stage of the investigation in conventional activated sludge process, the mixed liquor suspended solids concentration in the aeration tank was kept at about 2000 mg/L.Table 2 shows the steady-state data obtained in aeration tank, while Figs. 2 and 3 show the determination of the coefficients. The biokinetic coefficients were found to be as follows: Y=0.4872 mg VSS/mg sCOD, k_d=0.0258 1/day, K_S=52.1 mg sCOD/L and k=1.95 1/day. The effect of F/M on the removal efficiency of COD was significant, where COD removal was found to range between 83% and 92.5%.
Results of the steady-state conditions of the conventional process operating at MLSS concentration of 3000 mg/L, are presented in Table 3. In order to determine the biokinetic coefficients, Figs. 4 and 5 are plotted. The values of the biokinetic coefficients were found to be as follows: Y=0.804 mg VSS/mg sCOD, kd=0.0189

Table 2: Operational parameters at MLSS=2000 mg/L in aeration tank

Steady-state period	Q (L/h)	HRT (h)	MLVSS (mg/L)	sCODin (mg/L)	sCODout (mg/L)	SRT (day)	F/M (1/day)
1-12	38	7.89	1505	127.66	9.2	9.21	0.261
18-31	45	6.67	1316	145.48	13.18	7.097	0.403
36-50	56	5.36	1440	138.9	18.63	4.237	0.44
57-68	66	4.55	1442	128.43	21.64	3.15	0.479

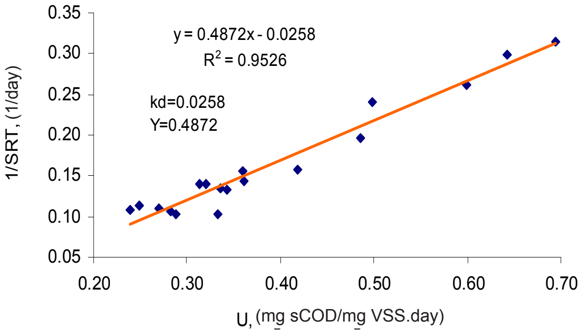

Fig. 2: Determination of Y and kd

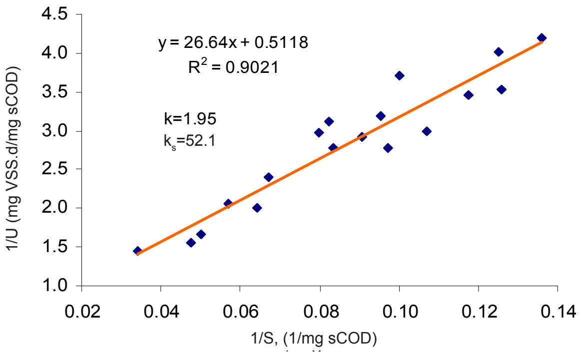

Fig. 3: Determination of K_s and k

Table 3. Steady-state data in MLSS concentration of 3000 mg/L

Steady-state period	Q (L/h)	HRT (h)	MLVSS (mg/L)	sCODin (mg/L)	sCODout (mg/L)	SRT (day)	F/M (1/day)
78-86	38	7.89	2127	110.2	8	12.25	0.158
93-101	42	7.14	2164	103.4	9.3	11.25	0.161
107-115	47	6.38	2057	106	13.4	9.23	0.195
120-129	54	5.56	2172	115.8	16	6.17	0.231
135-143	66	4.55	2232	128	19.9	5.04	0.303

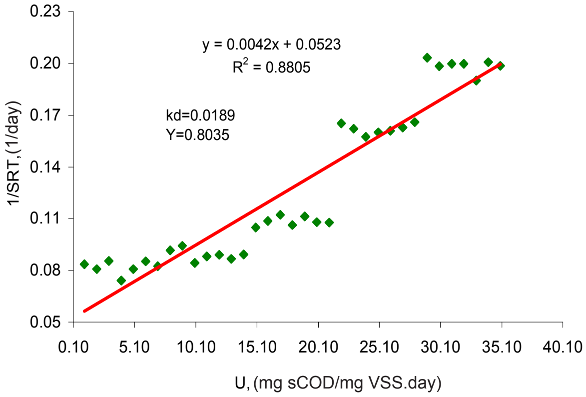

Fig. 4: Determination of Y and k_d

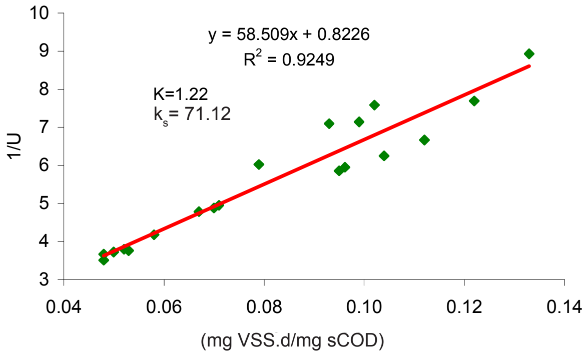

Fig. 5: Determination of K_s and k

1/day, K_S=71.12 mg sCOD/L and k=1.22 1/day. The effect of F/M on the removal efficiency of COD was significant, where COD removal was found to range between 84.4% and 92.7%.

Extended aeration activated sludge process

During the first stage of the investigation in exetended aeration process, the mixed liquor suspended solids concentration in the aeration tank was kept at about 4000 mg/L. Table 4 shows the steady-state data obtained at MLSS concentration of 4000 mg/L, while Figs. 6 and 7 show the determination of the coefficients. The biokinetic coefficients were found to be as follows: Y=0.6182 mg VSS/mg sCOD, k_d=0.0308 1/day, K_S=311.7 mg sCOD/L and k=3.17 1/day. The effect of F/M on the removal efficiency of COD was not significant, where COD removal was found to range between 88% and 92.5%.

During the second phase, the MLSS concentration was increased to 5000 mg/L. Table 5 shows data obtained at steady-state conditions and Figs. 8 and 9 show the determination of biokinetic coefficients. The values of the biokinetic coefficients obtained at MLSS of 5000 mg/L were as follows: Y=1.25 mg VSS/mg sCOD, k_d=0.0198 1/day, K_S=508 mg sCOD/L and k=2.53 1/day. The effect of F/M on the removal efficiency of COD was not significant, where COD removal was found to range between 91.3% and 93.76%.

Contact sabilization activated sludge process

During the first stage of the investigation in contact stabilization process, MLSS in the contact and stabilization tanks, were kept at about 2000 and 5000mg/L, respectively. Table 6 shows the

Table 4: Steady-state data at MLSS=4000 mg/L in the aeration tank

Steady-state period	Q (L/h)	HRT (h)	MLVSS (mg/L)	sCODin (mg/L)	sCODout (mg/L)	SRT (day)	F/M (1/day)
1-12	11	27.27	1795	175	13.09	40.18	0.087
18-31	12	25	2167	216.32	16.77	35.36	0.101
36-53	13	23.08	2298	223.9	19.2	25.26	0.101
59-72	14	21.43	1866	214.57	25.17	23.11	0.129
78-89	15	20	1864	171.63	16.95	20.37	0.111

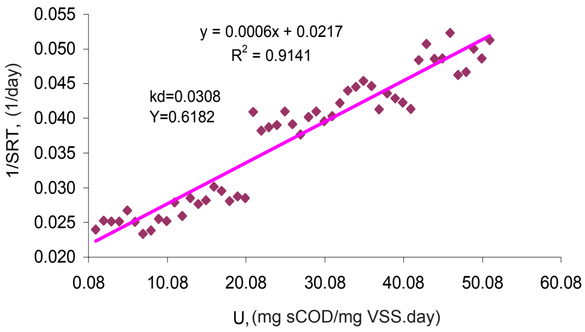

Fig. 6: Determination of Y and kd

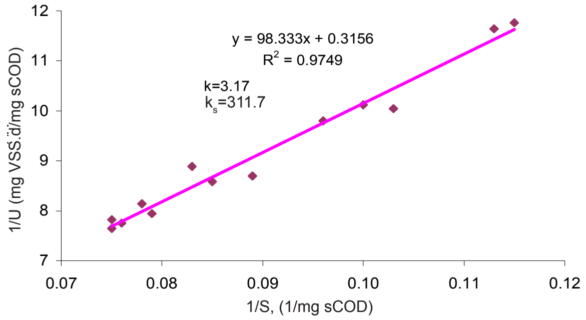

Fig. 7: Determination of K_s and k

Table 5. Operational parameters in MLSS=5000 mg/L aeration tank

Steady-state period	Q (L/h)	HRT (h)	MLVSS (mg/L)	sCODin (mg/L)	sCODout (mg/L)	SRT (day)	F/M (1/day)
95-101	11	27.27	2886	123.76	7.66	40.48	0.038
107-113	12	25	2820	134.2	9.23	35.9	0.046
117-123	13	23.08	2980	135.25	10.89	25.4	0.047
129-135	14	21.43	3053	147.07	12.9	22.47	0.054
138-143	16	18.75	3131	150.88	11.9	20.38	0.062

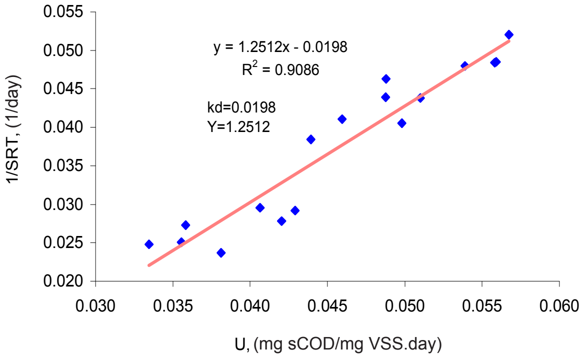

Fig. 8: Determination of Y and k_d

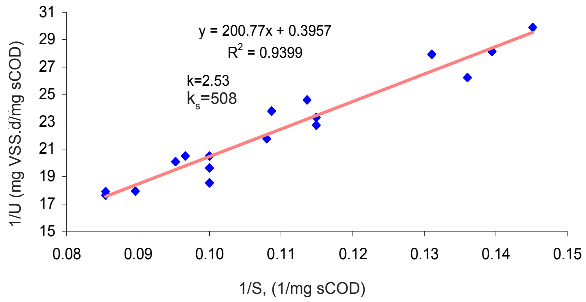

Fig. 9: Determination of K_s and k

steady-state data obtained at MLSS of 2000 mg/L in the contact tank, while Figs. 10 and 11 show the determination of the coefficients. The biokinetic coefficients were found to be as follows: Y=0.713 mg VSS/mg sCOD, k_d=0.0172 1/day, K_S=50.8 mg sCOD/L and k=0.586 1/day. The effect of F/M on the removal efficiency of COD was significant, where COD removal was found to range between 77% and 91.7%.

During the second phase, MLSS in the contact and stabilization tanks were increased to 3000 and 6000 mg/L, respectively. Table 7 shows data obtained at steady-state conditions and Figs. 12 and 13 show the determination of biokinetic coefficients. The values of the biokinetic coefficients obtained at an MLSS of 3000 mg/L were as follows: Y=0.63 mg VSS/mg sCOD, k_d=0.0387 1/day, K_S=13.8 mg sCOD/L and k=0.366 1/day. The effect of F/M on the removal efficiency of COD was significant, where COD removal was found to range between 77.86% and 92%.

DISCUSSION

Based on the biokinetic results that are shown in Figs. (2-13), Table 8 presents a summary of the biokinetic coefficients obtained for three activated sludge processes and for two MLSS values in each process. The Table clearly shows that values of the biokinetic coefficients vary significantly

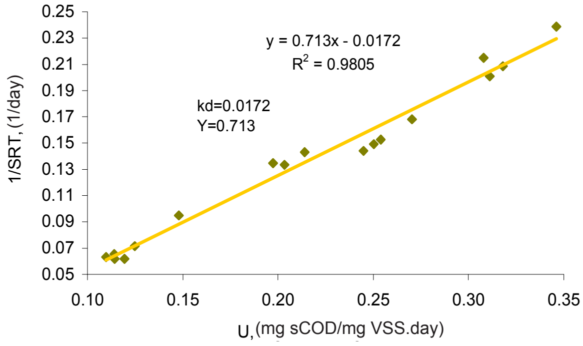

Fig. 10. Determination of Y and kd

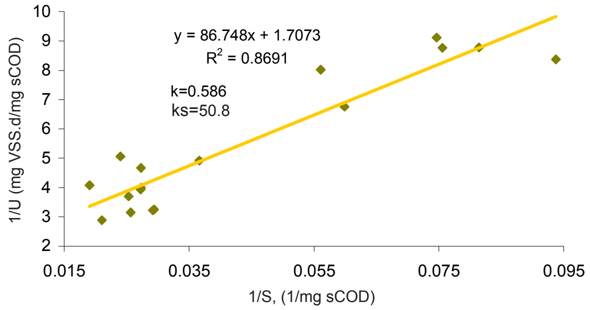

Fig. 11. Determination of K_s and k

Table 6. Steady-state data in MLSS of 2000 mg/L in contact tank

Steady-state period	Q (L/h)	HRT (h)	MLSS (mg/L)	MLVSS (mg/L)	sCODin (mg/L)	sCODout (mg/L)	SRT (day)	F/M (1/day)
1-12	53	1.015	1832	1199	175	14.7	15.44	0.241
18-31	63	0.85	1906	1249	216.32	31.25	10.6	0.355
36-53	75	0.717	1935	1275	223.9	34.93	7.1	0.42
59-72	88	0.609	1773	1181	214.57	43.99	6.26	0.546
78-89	103	0.522	1794	1172	171.63	39.68	4.486	0.526

Table 7: Steady-state data at MLSS of 3000 mg/L in contact tank

Steady-state period	Q (L/h)	HRT (h)	MLVSS (mg/L)	sCODin (mg/L)	sCODout (mg/L)	SRT (day)	F/M (1/day)
95-101	56	0.96	2077	123.76	9.83	18.3	0.16
107-113	62	0.87	1994	134.18	13.36	13.5	0.189
117-123	74	0.73	2068	135.25	19.6	10.2	0.212
129-135	85	0.63	2071	147.07	26.9	9.35	0.294
138-143	100	0.54	2223	150.88	33.42	7.39	0.453

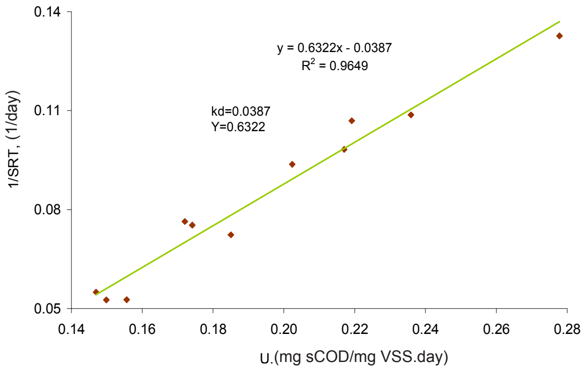

Fig. 12. Determination of Y and k_d

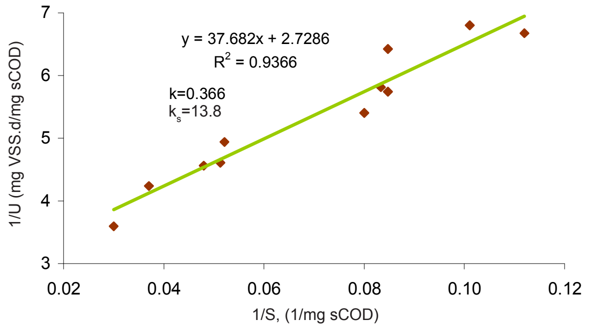

Fig. 13. Determination of K_s and k

with the change in MLSS concentration in each process. Hovever, this variability does not follow any definite pattern. This could be attributed to the nature of the process itself, as it could be a selective one and the biokinetic coefficients obtained may represent different species .

Generally, values of the biokinetic coefficients presented in Table 8 for conventional activated sludge process (Figs. 2-5) are within the normal range reported for the conventional activated sludge processes.

Table 9 summarizes some of the biokinetic coefficients obtained from different sources. Other values for the biokinetic coefficients can be found in Benefield and Randall (Benefield and Randall, 1980) and Grady and Lim (Grady and Lim, 1980).

Although, Y, k_d, K_s and μ_{max} coefficients for conventional process are within the reported values for conventional activated sludge processes, they differ quite significantly. The values of Y in conventional process were increasing with the increase in MLSS concentrations, since they represent all the amount of biomass produced by the growth during the removal of the substrate. This clearly shows that the type of substrate and bacterial can have a significant effect on the determination of the biokinetic coefficients. On the other hand, k_d was found to decrease with the increase in the MLSS concentration, which could indicate that the amount of sludge produced at higher MLSS values is not reduced. Increasing the MLSS concentration was also found to increase the maximum rate of growth of the biomass and saturation constant, which could be also attributed to the same reason given before.

Values of the biokinetic coefficients presented in Table 8 for extended aeration process, except for K_s and Y in MLSS=5000 mg/L, are within the normal range reported for the conventional activated sludge processes. Values of K_s, especially at MLSS of 5000 mg/L, were much higher than those reported in the literature (Table 9). This is attributed to the fact that the determination of the K_s is affected by estimation of the decay rate, k_d, thus any uncertainty in estimating k_d will be reflected on the K_s value. In this system also values of Y were increasing with the increase in MLSS concentrations. Values of Y at MLSS

Table 8: Monod kinetic coefficients for three activated sludge processes at different MLSS concentrations

Process	MLSS (mg/L)	Y (mg/mg)	K_d (1/day)	K_s (mg /L)	k (1/day)	μ_{max} (1/day)
Conventional	2000	0.4872	0.0258	52.1	1.95	0.95
	3000	0.8035	0.0189	71.12	1.22	0.98
Extended aeration	4000	0.6174	0.0309	311.7	3.17	1.96
	5000	1.2512	0.0198	508	2.53	3.17
Contact stabilization	2000	0.713	0.0172	50.8	0.586	0.42
	3000	0.6322	0.0387	13.8	0.366	0.23

Table 9: Kinetic coefficients obtained from different sources at COD

Substrate	Y (mg/mg)	kd (1/day)	μ_{max} (1/day)	Ks (mg /L)	Source
Domestic	0.31-0.35	0.016-0.068	1.7	43-223	Pala, 2005
Domestic	0.67	0.07	3.75	22	Lawrence, 1970
Glucose	0.5-0.62	0.025-0.48	7.4-18.5	11-181	Al-Malack, 2006
Synthetic	0.42-0.53	0.05-0.19	0.8-6.3	83-646	Al-Malack, 2006
MWW	0.46-0.6	0.05-0.16	5.6-8.1	250-3720	Al-Malack, 2006
MWW	0.4-0.8	0.025-0.075	2-10	15-70	Metcalf&Eddy, 1991
Domestic	0.4-0.67	0.07-0.09	3.2-3.75	22-60	Pala, 2005
Synthetic	0.49-0.58	0.037-0.151	1.28-6.46	289-2933	Al-Malack, 2006
MWW	1.78	0.12	0.28	36.6	Joseph, 1999
MWW	0.67	0.5	1.86	65.5	Naghizadeh, 2008
MWW	0.49-0.804	0.019-0.026	0.95-0.98	52-71.12	This study (conventional)
MWW	0.62-1.25	0.02-0.031	1.96-3.17	311.7-508	This study (extended aeration)
MWW	0.63-0.713	0.017-0.039	0.23-0.42	13.8-50.8	This study (contact stabilization)

of 5000 mg/L were much higher than those reported in the literature (Table 9). This clearly shows that the type of substrate and bacterial can have a significant effect on the determination of the biokinetic coefficients. Sludge retention time was high in extended aeration system, that cause reduction in substrate. The presence of many vorticella coloni, rotifer and nematode in this SRT in substrate at MLSS of 5000 mg/L, increases the yield coefficient (Y). Increasing the MLSS concentration was also found to increase the maximum rate of growth of the biomass and saturation constant, which could be also attributed to the same reason given before.

Values of the biokinetic coefficients presented in Table 8 for contact stabilization process, except that for μ_{max}, are within the normal range reported for the conventional activated sludge processes. The values of Y in contact stabilization process were decreasing with the increase in MLSS concentrations, because the amount of biomass produced by the growth during the removal of the substrate in stabilization tank decreases with increasing in MLSS concentration. On the other hand, k_d was found to increase with the increase in the MLSS concentration, which could indicate that the amount of sludge produced at higher MLSS values is reduced. Increasing the MLSS concentration was also found to decrease the maximum rate of growth of the biomass and saturation constant, which could be also attributed to the same reason given before.

In order to determine which biokinetic parameter has the greatest influence on the effluent substrate concentration, a sensitivity analysis was performed. The values of each of the k_d, μ_{max}, and K_s were individually varied by ± 50%, while the other parameters were kept constant. The sludge

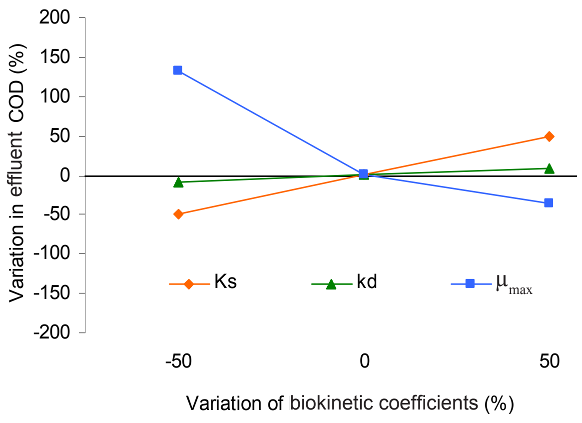

Fig. 14. Sensitivity at MLSS of 2000mg/L

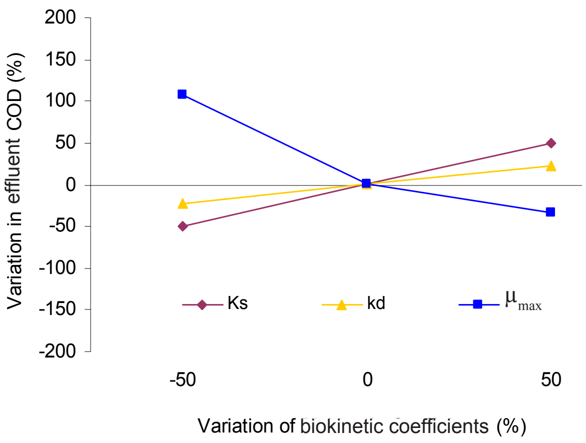

Fig. 16. Sensitivity at MLSS of 4000mg/L

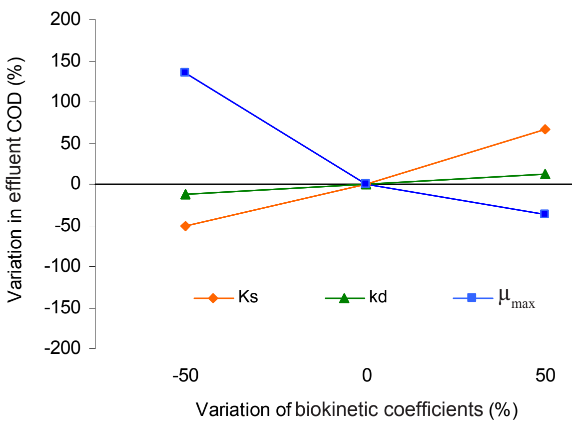

Fig. 15. Sensitivity at MLSS of 3000mg/L

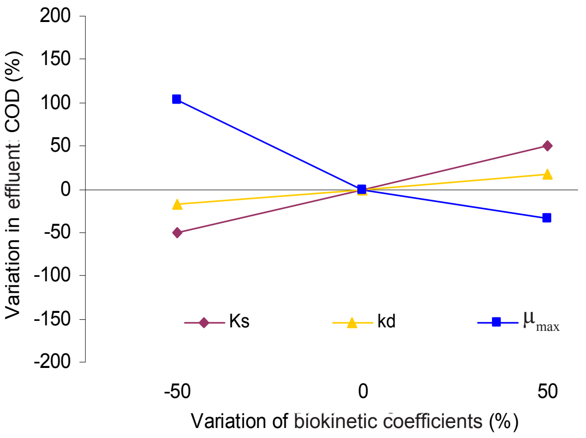

Fig. 17. Sensitivity at MLSS of 5000mg/L

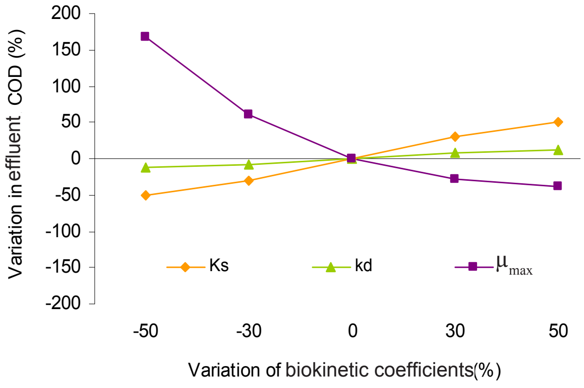

Fig. 18. Sensitivity at MLSS of 2000mg/L

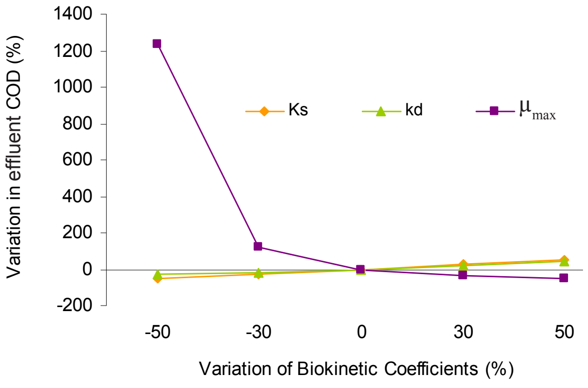

Fig. 19. Sensitivity at MLSS of 3000mg/L

retention time in conventional activated sludge, extended aeration and contact stabilization systems were kept at 10, 25 and 15 days, respectively, during the sensitivity analysis. The sensitivity of the various biokinetic coefficients was studied by simulating the effluent COD. The result of the sensitivity analysis are shown in Figs. (14-19): Figs. (14,15) for conventional process, Figs. (16,17) for extended aeration process and Figs. (18,19) for contact stabilization process. It can be clearly seen that k_d and K_s are directly proportional to the effluent substrate concentration, while μ_{max} is inversely proportional to the effluent substrate concentration. Regardless of the MLSS concentration, the effluent substrate concentration was found to be more sensitive to μ_{max} when compared to k_d and K_s.

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