Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2016.1192566

57 (2016) 28600–28609
December

Taylor & Francis
Taylor & Francis Group

Biokinetic coefficients of anaerobic immersed membrane bioreactor (AnIMBR) treating dairy wastewater

Muhammad H. Al-Malack*, Gerardo R. Aldana

Civil and Environmental Engineering Department, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia, email: mhmalack@kfupm.edu.sa (M.H. Al-Malack)

Received 19 February 2016; Accepted 16 May 2016

ABSTRACT

In order to determine biokinetic coefficients, namely, cell yield (Y), maximum specific growth (μ_m), endogenous decay coefficient (k_d), and saturation constant (K_s), a lab-scale anaerobic immersed membrane bioreactor (AnIMBR) was used. The AnIMBR was performed at different values of mixed liquor suspended solids (mixed liquor suspended solids (MLSS) values of 5,000, 10,000, and 15,000 mg/L) and influent chemical oxygen demand (chemical oxygen demand (COD) values of 2,000, 4,000, 6,000, and 8,000 mg/L). The results showed that Y, μ_m, k_d, and K_s were in the ranges of 0.2022–0.427 mg/mg, 0.0334–0.1095 (1/d), 0.0009–0.0022 (1/d), and 4612–6663 (mg COD/L), respectively. Values of Y, μ_m, and k_d were in the range of those reported in the published literature for various anaerobic processes using different substrates. However, values of K_s, obtained from the current investigation, were higher than those reported in the published literature. This can be attributed to the fact that by increasing the influent COD and decreasing the MLSS concentrations, the process removal efficiency will decrease and in turn, K_s will increase. Effluent COD at different values of MLSS was simulated and sensitivity analysis showed that the process performance was more sensitive to K_s than other biokinetic coefficients.

Keywords: Effluent COD; Cell yield; Endogenous decay coefficient; Specific growth rate; Saturation constant; Performance sensitivity

1. Introduction

In design of biological wastewater treatment processes, biological parameters such as growth of biomass, rate of food consumption, and mean cell residence time need to be determined, therefore, equations of biological kinetics are used. Biomass growth, substrate utilization, reactor volume, and effluent quality can be determined from those biokinetic equations. Biokinetic coefficients used in the design of aerobic and anaerobic biological wastewater treatment processes include specific growth rate (μ), endogenous decay coefficient (k_d), maximum rate of substrate utilization per unit mass of microorganisms (k), maximum cell yield (Y) and half-velocity constant, or substrate concentration at one-half the maximum specific growth rate (K_s). Anaerobic membrane bioreactor (AnMBR) is a combination of anaerobic biodegradation and membrane technology. Immersed or submerged AnMBRs have the advantage of occupying less footprints in addition to reduced energy intake, reduced membrane cleaning frequencies, and

*Corresponding author.

reduced sludge production. Zamanzadeh et al. conducted biokinetic and molecular investigations of methanogens in phased anaerobic digestion systems [1]. They investigated the effect of operational parameters on biokinetic coefficients of methanogenic archaea. The results showed that operational temperature had dramatic effect on communities of archaea. They reported that the maximum specific rates of substrate consumption (k_{max}) of methanogens in mesophilic and thermophilic environments were 11.4–22.0 mg COD per mg COD per day, respectively. They also reported values of K_s between 124 ± 50 and 560 ± 64 mg COD/L for both phases of the anaerobic digestion process. Kim et al. investigated effects of temperature and pH on the biodegradation biokinetic of thiocyanate using mixed-culture autotrophs [2]. Three kinetic coefficients, namely, maximum specific growth rate (μ_m), saturation coefficient (K_s), and substrate inhibition coefficient (K_{si}) were determined in the investigation. The results indicated that temperature and pH had dramatic effects on values of biokinetic coefficients, particularly maximum specific growth rate (μ_m). Moreover, they reported values of maximum specific growth rate (μ_m) and saturation coefficient (K_s) between 0.29 to 0.495 (per day) and 74.9 to 171.1 (mg SCN per liter), respectively. Mardani et al. determined biokinetic coefficients, namely, specific growth rate (μ), endogenous decay coefficient (k_d), maximum rate of substrate utilization per unit mass of microorganisms (k), maximum cell yield (Y), and half-velocity constant for three types of activated sludge processes, namely, conventional, extended aeration, and contact stabilization [3]. They reported values between 0.49 to 1.25 (mg/mg), 0.017 to 0.039 (per day), 0.23 to 3.17 (per day), 13.8 to 508 (mg/L), and 0.366 to 3.17 (per day) for Y, k_d, μ_m, K_s, and k, respectively. More work on the determination of biokinetic coefficients can be cited in the published literature [4–6]. In the published literature, Table 1 shows that several investigators determined biokinetic coefficients for different aerobic and anaerobic processes when treating different types of wastewaters; however, it is very clear that there is a lack of information with respect to anaerobic immersed membrane bioreactors treating dairy wastewater [7–18]. Based on the above discussion, the main objective of the current investigation is to determine the biokinetic coefficients of an anaerobic immersed membrane bioreactor (AnIMBR) treating synthetic dairy wastewater. Biokinetic coefficients were determined at different values of mixed liquor suspended solids (MLSS) (5,000, 10,000, and 15,000 mg/L) and influent chemical oxygen demand (COD) concentrations (2,000, 4,000, 6,000, and 8,000 mg/L).

1.1. Determination of biokinetic coefficients

Equations describing growth of microorganisms and substrate utilization in anaerobic communities are based on Monod equations; however, several investigators such as Teissier [19], Contois [20], and Moser [21] have proposed other expressions. Nowadays, Monod's model is still considered as one of the most widely used for the study of anaerobic biokinetic coefficients [1,22–24]. Moreover, the IAWPRC task group recognized Monod equation as the fundamental basis for growth of microorganisms [25]. Microorganisms require substrate for three main functions, namely, synthesis of new cell material, synthesis of extra-cellular products, and provision of sufficient energy needed for cell maintenance. Fig. 1 shows a schematic diagram of a completely mixed AnIMBR, where the following assumptions were made:

(1) Completely mixed reactor.
(2) Constant reactor volume.
(3) Complete rejection of MLSS by membrane module.
(4) Zero rejection of substrate membrane module.
(5) Zero microbial mass in influent substrate.

Performance of the AnIMBR can be well described by the following biomass and substrate mass balance equations:

Biomass balance

$$\begin{bmatrix}\text{Rate of change}\\ \text{of biomass in}\\ \text{reactor}\end{bmatrix} = \begin{bmatrix}\text{Rate of change}\\ \text{due to growth}\end{bmatrix} - \begin{bmatrix}\text{Rate of change due to}\\ \text{endogenous decay}\end{bmatrix} - \begin{bmatrix}\text{Deliberate}\\ \text{wastage}\end{bmatrix}$$

The mathematical illustration of the above expression is:

$$V\frac{dX}{dt} = \mu XV - k_d XV - Q_w X \quad (1)$$

where V is the reactor volume (L), X is the biomass concentration inside the reactor (mg/L), μ is the specific growth rate (per day), and Q_w is the wastage flow (L/d). For steady-state conditions ($dX/dt = 0$), Eq. (1) can be rewritten as follows:

$$\mu = k_d + \frac{Q_w}{V} \quad (2)$$

Table 1
Biokinetic coefficients for biological processess using different substrates

Substrate	Y (mg/mg)	K_d (d^{-1})	μ_m (d^{-1})	K_s (mg COD/L)	System	Refs.
Dairy	0.2281	0.1383	1.69	174	MSBR	[7]
Coconut cream	0.1383	0.0008	0.32	8,000	–	[8]
Domestic	0.36	ND	0.008	ND	MSBR	[9]
Cassava starch	ND	ND	3.12	ND	–	[10,11]
Acetate	ND	0.014	ND	ND	–	[12]
Dairy	ND	ND	0.44	141	AS	[13]
Dairy	0.153	0.022	ND	ND	UASB	[14]
Dairy	0.29	0.14	9.9	134	2-phase AnD	[15]
Dairy	0.2116	0.0131	0.7844	420.8	AnD	[16]
Glucose	0.31	1.56	64.8	2,583	AnD	[17]
Acetate	0.027–0.057	0.0036–0.006	0.038–0.4	ND	AnD	[17]
Pesticide	0.148	0.05	3.37	4,077	AnD	[18]

Notes: ND: Not Determined; AnD: Anaerobic Digestion.

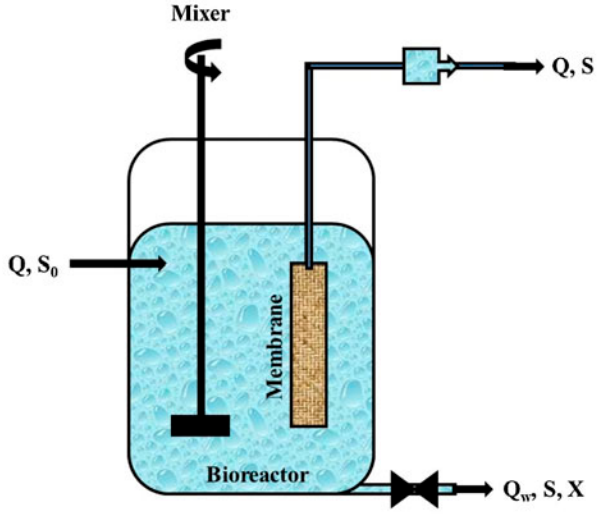

Fig. 1. Schematic diagram of the completely mixed AnIMBR.

Since the sludge retention time (SRT) is defined as:

$$\mathrm{SRT} = \frac{\text{Total biomass in the reactor}}{\text{Total biomass leaving the system per day}}$$

It can be written as:

$$\mathrm{SRT} = \frac{VX}{Q_w X} = \frac{V}{Q_w} \tag{3}$$

Rearranging and substituting Eq. (3) into Eq. (2), the following expression is obtained:

$$\mu = k_d + \frac{1}{\mathrm{SRT}} \tag{4}$$

Using Monod equation:

$$\mu = \mu_m \frac{S}{K_s + S} \tag{5}$$

where μ_m is the maximum specific growth rate (per time), S is the concentration of substrate (food) available to biomass (mass per unit volume), k_s is the saturation constant (mass per unit volume). Substituting Eq. (5) in Eq. (4), the substrate concentration (S) in the reactor at steady-state condition can be obtained:

$$S = \frac{K_s\left(\frac{1}{\mathrm{SRT}} + k_d\right)}{\mu_m - \left(\frac{1}{\mathrm{SRT}} + k_d\right)} \tag{6}$$

Substrate balance

$$\begin{bmatrix}\text{Rate of change of substrate in the reactor}\end{bmatrix} = \begin{bmatrix}\text{Rate of input of the feed substrate}\end{bmatrix} - \begin{bmatrix}\text{Removal rate due to biomass utilization}\end{bmatrix} - \begin{bmatrix}\text{Removal rate due to washout}\end{bmatrix} - \begin{bmatrix}\text{Substrate loss during deliberate wastage of biomass}\end{bmatrix}$$

Mathematical representation of the above expression is:

$$V\frac{dS}{dt} = QS_0 - \mu\frac{XV}{Y} - S(Q - Q_w) - Q_wS \quad (7)$$

If steady state prevails, then $dS/dt = 0$, and, consequently, Eq. (7) becomes:

$$\frac{Q}{V}(S_0 - S) = \mu\frac{X}{Y} \quad (8)$$

Substituting Eq. (4) into Eq. (8), the biomass concentration (X) at steady-state condition can be obtained:

$$X = Y\,\frac{Q(S_0 - S)}{k_d + \frac{1}{SRT}} \quad (9)$$

2. Materials and methods

2.1. Experimental setup

The experimental setup of the anaerobic immersed membrane bioreactor that was used throughout the investigation period comprised mainly of feed tank, anaerobic bioreactor, membrane module, gas collection system, and permeate tank. Mechanical mixer was used to mix the contents of the anaerobic bioreactor, while peristaltic pump and pressure gages were used to withdraw the permeate and measure suction and backwashing pressures, respectively. The schematic diagram of the AnIMBR that was used throughout the investigation can be cited in Al-Malack and Aldana who investigated the performance of anaerobic immersed membrane bioreactor (AnIMBR) treating synthetic dairy wastewater [26]. Table 2 shows the general characteristics of the membrane module that was used in the investigation.

2.2. Synthetic dairy wastewater

After a thorough literature survey about the general and main characteristics of dairy wastewater, COD, biochemical oxygen demand (BOD_5), pH, total phosphorous (TP), total Kjeldahl nitrogen (TKN), total solids (TS), total suspended solids (TSS), and total dissolved solids (TDS) beside other parameters were taken into consideration when the synthetic dairy wastewater was prepared. Table 3 shows the general characteristics of the synthetic dairy wastewater, where powder milk was used in the preparation of the dairy wastewater.

2.3. Chemical analysis

Influent and permeate samples were collected and subjected to chemical analysis in accordance with the Standard Methods [27]. Moreover, pH of the anaerobic reactor was monitored and maintained at values between 6.8 and 7.2.

3. Results and discussion

In completely mixed continuous-flow reactors, determination of biokinetic coefficients is accomplished through data collection from lab- or pilot-scale processes. In these cases, systems are operated at different hydraulic retention times (HRTs) or SRTs and allowing steady-state conditions to prevail, therefore, precise data on biomass and permeate substrate concentrations are collected. Biokinetic coefficients, namely, k_s, μ, Y, and k_d can be determined using linear forms of Eqs. (6) and (9), where Eq. (10) is used for the determination of k_d and Y, while Eq. (11) is used for the determination of μ_m and K_s:

$$\frac{Q}{VX}(S_0 - S) = \frac{1}{Y}\frac{1}{SRT} + \frac{k_d}{Y} \quad (10)$$

$$\frac{SRT}{1 + SRTk_d} = \frac{K_s}{\mu_m}\frac{1}{S} + \frac{1}{\mu_m} \quad (11)$$

Plotting $\frac{Q}{VX}(S_0 - S)$ vs. $1/SRT$ (Eq. (10)), kinetic coefficients Y and k_d, can be determined from slope and y-intercept of the produced lines, respectively. Obtained k_d values can then be used in Eq. (11) to plot $\frac{SRT}{1+SRTk_d}$ vs. $1/S$. Kinetic coefficients K_s and μ_m can be found from slope and y-intercept, respectively, of the produced plots. Determination of biokinetic coefficients for the constant-flux AnIMBR was accomplished using SRTs since HRTs were almost constant. The AnIMBR process was operated at different concentrations of MLSS and influent COD concentration. It is worth to mention that in order to reach the pre-designed MLSS concentrations, wasting of different volumes of biomass from the bioreactor was performed on daily basis. Steady-state conditions were assumed to be reached when sludge growth and permeate COD values were almost constant with no significant fluctuations. It is worth mentioning that SRT and organic loading rates (OLR) values were calculated using the following Equations:

$$SRT = \frac{V_rX_{avg}}{V_wX_{inc}} \quad (12)$$

Table 2
General characteristics of membrane module

Parameter	Units	VFU-250a	Remarks
Water flux	l/m^2h 100 kPa	>500	At 25℃ and 100 kPa
Molecular weight cut off	Da	250,000	Dextrane mixture
Temperature range	℃	1–70	At pH 7 and 100 kPa
Pore size	μm	0.03–0.05	
pH range		2–10	At 25℃
Diameter "outer side"	mm	9.2	
Length	mm	340	Only tubes
Total length	mm	400	
Total membrane area	m^2	0.04	
Permeate outlet with hose nozzle	mm	9	
Filtration direction		From outside to inside	Submerged
Type	UF tubular		
Membrane material	PVDF		
Manufacturer	Membrane modules systems (MEMOS)		

Table 3
General characteristics of synthetic wastewater

Constituent	Concentration (mg/L)[a]
pH	6.66
Turbidity (NTU)	1,500 ± 3
NH_4	<1
TS	1,980
TSS	1,213
TDS	767
BOD	1,341 ± 81
SCOD	940 ± 85
TCOD	2,950 ± 130
TKN	55.72 ± 1.68
Ca	227
K	69.4
Mg	62.9
Na	511
Fe	0.193
TP	8.7
PO_4^{3-}	6.24 ± 0.24

[a]Except pH and turbidity.

$$\mathrm{OLR} = \frac{\mathrm{COD_{inf}} Q}{V_r X_{avg}} \tag{13}$$

where V_r is the reactor volume (L), X_{avg} is the average value of MLSS (mg/L), V_w is the wasted sludge per day (L/d), X_{inc} is the value of MLSS before wasting (mg/L), $\mathrm{COD_{inf}}$ is the influent COD (mg/L), and Q is the influent flow rate (L/d).

The biokinetic investigation started with an MLSS concentration of 10,000 mg/L and influent COD concentration of 2,000 mg/L. At these conditions, the steady state was kept to prevail for 3 d, after which the influent COD was increased to 4,000, 6,000, and finally to 8,000 mg/L. It is worth to confirm that before shifting to the next influent COD concentration, steady-state conditions were allowed to prevail for 3–4 d. The same procedure was adopted with MLSS concentrations of 15,000 and 5,000 mg/L. Table 4 shows data on steady-state conditions obtained at MLSS values under investigation. On the other hand, Figs. 2 and 3 show graphical representations of Eqs. (10) and (11), respectively, that were used to compute the AnIMBR biokinetic coefficients for MLSS values of 5,000, 10,000, and 15,000 mg/L. From Figs. 2 and 3, biokinetic coefficients for MLSS value of 10,000 mg/L were: $Y = 0.2113$ mg/mg; $k_d = 0.0012\ d^{-1}$; $\mu_m = 0.0615\ d^{-1}$, and $K_s = 5{,}381$ mg COD/L. With respect to the process removal efficiency of COD, at an MLSS concentration of 10,000 mg/L, Al-Malack and Aldana, reported that maximum COD removal efficiencies accomplished for influent COD concentrations of 2,000, 4,000, 6,000, and 8,000 mg/L were 83, 87, 84, and 74%, respectively [26]. The results clearly show that the effect of increasing influent COD on COD removal efficiency was insignificant until the influent COD was increased to 8,000 mg/L, which could be attributed to the fact that the biomass (MLSS) could not cope with the available substrate (influent COD).

The process MLSS was then increased to 15,000 mg/L while influent COD concentrations remained similar to those used in the previous investigation (2,000, 4,000, 6,000, and 8,000 mg/L). Steady-state data at MLSS of 15,000 mg/L are presented in Table 4, while the determinations of biokinetic coefficients are shown in Figs. 2 and 3. Figs. 2 and 3 show

Table 4
Steady-state data at MLSS values of 5,000, 10,000, and 15,000 mg/L

Steady-state period (d)	Q (L/d)	X (mg/L)	S_0 (mg/L)	S (mg/L)	SRT (d)	$Q(S_0 - S)/VX$ (1/d)	1/SRT (1/d)	$1/S$ (L/mg)	SRT/(1 + SRT × k_d) (d)
MLSS = 5,000 mg/L									
1–5	2.12	5,006	2,000	1,050	420	0.0183	0.0024	0.000952	220.17
6–10	2.16	5,034	4,000	1,949	201	0.0400	0.0050	0.000513	140.14
11–16	2	5,035	6,000	2,652	109	0.0604	0.0091	0.000377	88.50
17–21	2.16	5,006	8,000	5,018	93	0.0585	0.0107	0.000199	77.58
MLSS = 10,000 mg/L									
23–28	2.04	10,014	2,000	336	502	0.0154	0.0020	0.002980	295.32
29–33	2.12	10,034	4,000	545	185	0.0332	0.0054	0.001834	147.02
34–38	2.12	10,048	6,000	965	113	0.0483	0.0089	0.001036	97.48
39–44	2.2	10,045	8,000	2,064	90	0.0591	0.0111	0.000485	79.75
MLSS = 15,000 mg/L									
53–57	2.05	15,027	2,000	232	275	0.0110	0.0036	0.004310	218.54
58–62	2.20	15,050	4,000	346	99	0.0243	0.0101	0.002893	90.35
63–67	2.20	15,000	6,000	603	74	0.0360	0.0135	0.001658	69.34
68–72	2.05	15,045	8,000	1,614	61	0.0396	0.0164	0.000620	57.82

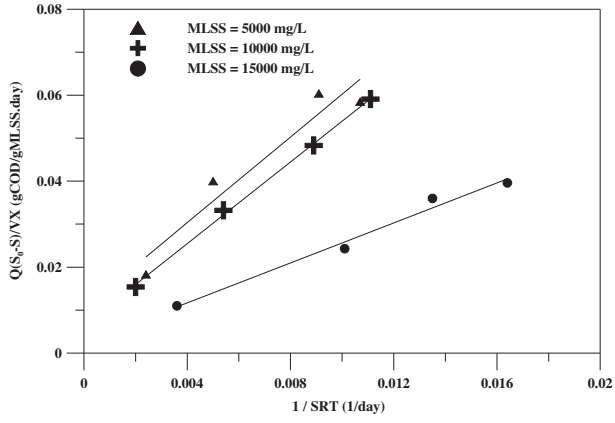

Fig. 2. Determination of Y and k_d values for MLSS values under investigation.

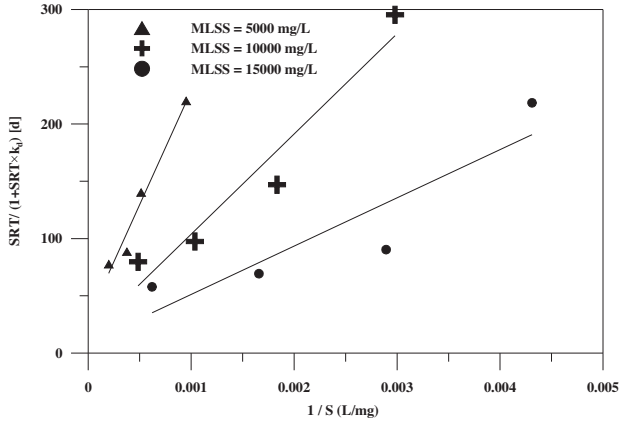

Fig. 3. Determination of μ_m and K_s values for MLSS values under investigation.

that biokinetic coefficients were: $Y = 0.4270$ mg/mg; $k_d = 0.0009\ d^{-1}$; $\mu_m = 0.1095\ d^{-1}$, and $K_s = 4{,}612$ mg COD/L. Results reported by Al-Malack and Aldana showed that when MLSS concentration was further increased to 15,000 mg/L, the maximum COD removal efficiencies were found to be 88, 91, 90, and 80% for influent COD concentrations of 2,000, 4,000, 6,000, and 8,000 mg/L, respectively [26]. The results clearly indicated that by increasing the MLSS from 10,000 to 15,000 mg/L, COD removal efficiencies have increased by marginal percentages (about 4%). This can be attributed to the fact that by increasing the MLSS concentration, the biomass concentration will, in turn, increase; therefore, more substrate (COD) will be consumed. However, it is recommended that higher influent COD concentrations must be considered for further investigation. Moreover, the results showed that COD removal efficiencies were observed to decrease when the COD concentration in the influent was further increased to 8,000 mg/L, which can be attributed to the same reasons given above.

During the third phase of the investigation, the process MLSS was decreased to 5,000 mg/L, while influent COD concentrations were kept the same as those implemented during the previous two phases of the investigation (2,000, 4,000, 6,000, and 8,000 mg/L).

Table 4 shows data obtained at steady-state conditions of the investigation, while Figs. 2 and 3 show the determination of the biokinetic coefficients. From Figs. 2 and 3, the biokinetic coefficients were: $Y = 0.2022$ mg/mg; $k_d = 0.0022$ d^{-1}; $\mu_m = 0.0334$ d^{-1}, and $K_s = 6{,}663$ mg COD/L. With respect to the COD removal efficiency at MLSS concentration of 5,000 mg/L, the results showed that the maximum removal efficiencies were 48, 51, 56, and 37% for influent COD concentrations of 2,000, 4,000, 6,000, and 8,000 mg/L, respectively [26]. The results clearly demonstrated that by decreasing the process MLSS concentration to 5,000 mg/L, the COD removal efficiency was found to decrease dramatically. This is a clear indication to the fact that by decreasing the MLSS concentration, the available biomass is becoming incapable of coping with the available substrate (influent COD). By decreasing the MLSS concentration from 10,000 to 5,000 mg/L, the COD removal efficiency was found to decrease significantly (about 30% less) [26]. In summary, the results clearly showed that the maximum COD removal efficiency at MLSS concentrations of 10,000–15,000 mg/L was achieved at an influent COD concentration of 4,000 mg/L, while at an MLSS of 5,000 mg/L, the maximum removal efficiency was accomplished at an influent COD of 6,000 mg/L. Moreover, the results clearly showed that when the influent COD concentration was increased to 8,000 mg/L, the COD removal efficiency was found to drop to 37, 74, and 80% for MLSS concentration of 5,000, 10,000, and 15,000 mg/L, respectively. This could be attributed to the incapability of the biomass to cope with the higher concentrations of substrate (influent COD) or higher OLRs.

Biokinetic coefficients determined from Figs. 2 and 3, for the three MLSS concentrations under investigation, are summarized and presented in Table 5. On the other hand, Table 6 presents a comparison between results of the current investigation and those reported in the published literature for anaerobic processes treating various types of wastewater. Table 5 clearly shows that biokinetic coefficients were varying with changes in MLSS concentrations, though yield coefficient (Y) values were almost constant at MLSS concentrations of 5,000–10,000 mg/L. The table also shows that endogenous decay coefficient (k_d) values were having low values, which indicates that death rates of the biomass were relatively slow. Moreover, obtained biomass maximum specific growth rates (μ_m) were also on the lower side when compared to values obtained from the published literature, particularly with aerobic processes [5]. The growth rate was demonstrated during the experimentation periods when MLSS concentrations exhibited low daily

Table 5
Summary of biokinetic coefficients for MLSS values under investigation

MLSS	Y (mg/mg)	k_d (d^{-1})	μ_m (d^{-1})	K_s (mg COD/L)
5,000	0.2022	0.0022	0.0334	6,663
10,000	0.2113	0.0014	0.0615	5,381
15,000	0.4270	0.0009	0.1095	4,612

increases, resulting in higher SRTs. Kaewsuk et al. reported that low bacterial growth rate and high K_s are correlated with low bacteria decay rate [28]. In comparison with values published in literature, Table 6 shows that values of Y, k_d, and μ_m obtained from the current investigation are within the ranges of those reported for anaerobic treatment of dairy wastewater and glucose. The only value that can be considered relatively high during all phases of the investigation is the half velocity constant, K_s, though close K_s values were reported in the published literature. In summary, Table 5 shows that as MLSS concentrations were increased, Y and μ_m were found to increase while k_d and K_s were found to decrease. However, due to insignificant changes of biokinetic coefficients with MLSS concentrations, it is not straightforward to come up with a definite and firm conclusion.

The value of K_s simply reflects the efficiency of the process to degrade organics, therefore, if low substrate concentration in the effluent is sought, low values of K_s are necessary [29]. In the current investigation, values of effluent substrate (COD) were relatively high; therefore, values of the half-velocity constant (K_s) are expected to be high. Lower values of K_s at higher MLSS values imply better performance of the AnIMBR process. Furthermore, this trend is accompanied by the increasing values of μ_m with the increasing MLSS concentrations, which indicates that the rate of biomass growth is faster; therefore, the demand of substrate consumption is increasing. Therefore, lower effluent substrate will be obtained leading to a better performance of the AnIMBR system that will result in decreasing the values of K_s.

Variations of kinetic coefficients at different MLSS concentrations could be attributed to several reasons. Firstly, the fact that the bioreactor contained a mixed culture rather than an isolated type of specific bacteria for the given substrate utilized throughout the investigation period. Secondly, the assumption of steady-state conditions for the development of Monod equations may have resulted in producing some errors when applying the biokinetic equations to real conditions, where several factors may have an affect the efficiency of the process. Furthermore, the use of SRT

Table 6
Comparison of biokinetic coefficients for anaerobic systems

Substrate	Y (mg/mg)	k_d (d^{-1})	μ_m (d^{-1})	K_s (mg COD/L)	System
Dairy/Glucose	0.027–0.31	0.003–1.56	0.038–64.8	141–4,077	Several
Dairy (Current investigation)	0.2022–0.427	0.0009–0.0022	0.0334–0.1095	4,612–6,663	AnIMBR

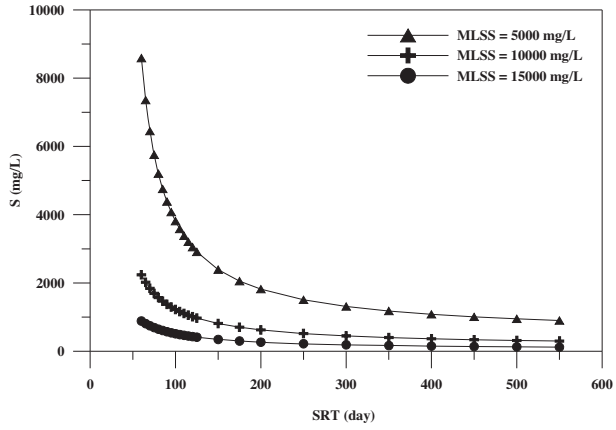

Fig. 4. Simulated Effluent COD for MLSS values under investigation.

as an alternative to HRT in the development of the biokinetic equations and during the investigation to determine the biokinetic coefficients, under investigation, could make a difference. This is because at specific MLSS concentration, different SRTs values will result in the flourish of different species of bacteria as predominant species in mixed-culture processes.

3.1. Simulation of steady-state conditions

To validate Monod's equations, a simulation of Eq. (6) was performed and plotted in Fig. 4. During the development of the equations, it was assumed that the AnIMBR was running under steady-state conditions. Therefore, Eq. (6) can be utilized to predict effluent COD concentrations at different MLSS concentrations and SRT values. Consequently, determined biokinetic coefficients were used in Eq. (6) to reproduce the simulated effluent COD concentrations at different SRT and MLSS values. Fig. 4 clearly demonstrates the trend that is followed by the predominant bacterial species when varying SRT values at certain fixed MLSS concentrations. Moreover, the figure clearly shows that higher SRT values produced higher effluent COD removal efficiencies till it reached a maximum SRT beyond which no change in effluent COD removal efficiency was observed. For MLSS concentrations of 10,000–15,000 mg/L, the maximum SRT was found to be 300 d, while it was 550 d for an MLSS concentration of 5,000 mg/L. This can be attributed to the fact that by increasing SRT values biomass (bacteria) will be fully grown and, therefore, degradation of available substrate (COD) takes place at faster rates. This was found to continue until a point where further increases in SRT values was found to result in accumulation of old bacteria that would complicate the easy access to the available substrate (COD) in the bioreactor, which will in turn result in limiting the removal efficiency of the substrate (COD). Another reason could be attributed to the fact that the bioreactor process has reached the maximum COD removal that can be achieved due to the presence of an irremovable COD (non-biodegradable COD) portion in the influent.

3.2. Sensitivity analysis

In order to assess the influence of the determined biokinetic coefficients on the effluent COD concentration, a sensitivity analysis was performed using the obtained results. Values of k_d, K_s, and μ_m were modified by ±50% individually, while keeping other biokinetic parameters constant. The analysis was performed by making use of Eq. (6) with the modified parameters in order to simulate the effluent COD concentrations as shown in Figs. 5, 6, and 7 for the different MLSS concentrations.

In general, the Figures clearly indicate that k_d and K_s are directly proportional to the simulated effluent COD, while μ_m is inversely proportional. Regardless of the MLSS concentration, the figures reveal that effluent COD concentrations displayed more sensitiveness to K_s when compared to other biokinetic parameters. Moreover, the results showed that by increasing the MLSS concentration, the effluent COD concentration was found to be less sensitive to all parameters. Thus, it can be deduced that at higher MLSS concentrations, effluent COD concentrations are less sensitive to variations in biokinetic coefficients. Nevertheless, caution should be taken when working with μ_m because small variations could result in producing wrong results. For example, when μ_m was modified

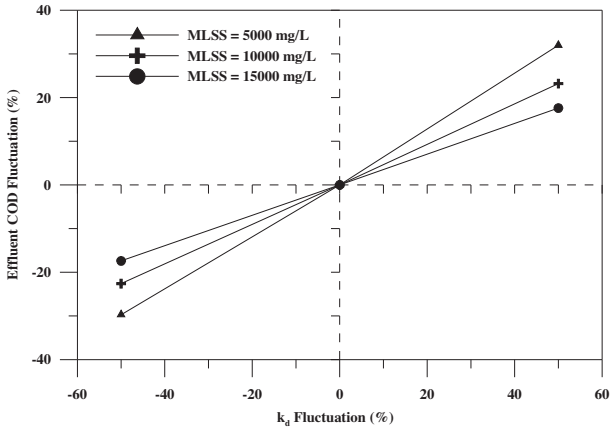

Fig. 5. Sensitivity analysis of k_d for MLSS values under investigation.

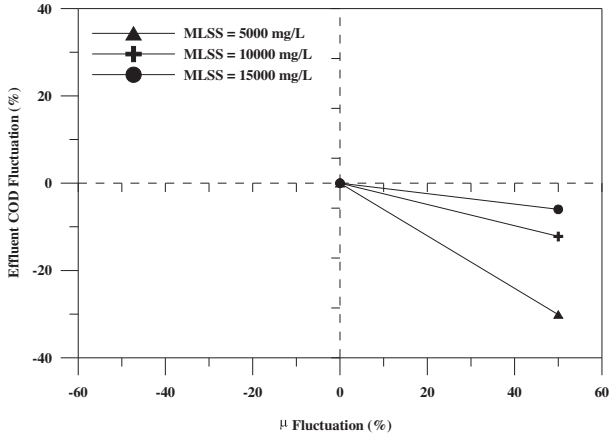

Fig. 6. Sensitivity analysis of μ_m for MLSS values under investigation.

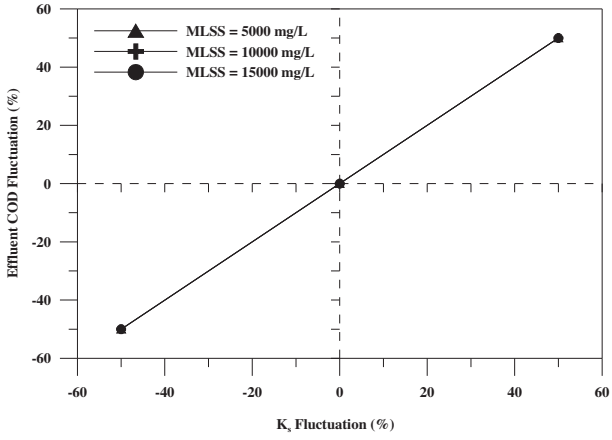

Fig. 7. Sensitivity analysis of K_s for MLSS values under investigation.

by (–50)%, the effluent COD concentration was found to vary greatly with no specific trend, therefore, these results were not included in the figures.

4. Conclusions

Synthetic dairy wastewater was treated using a lab-scale experimental setup. The investigation aimed at the determination of biokinetic coefficients, namely, cell yield (Y), maximum specific growth rate (μ_m), endogenous decay coefficient (k_d), and saturation constant (K_s). The investigation was conducted at various values of MLSS and influent COD. Results of the investigation clearly showed that the obtained values of Y, μ_m, and k_d were in the ranges of those reported in the published literature for anaerobic treatment processes of different wastewaters. However, K_s values were found to be relatively higher than those reported in the published literature, which could be attributed to estimations that were made during the determination of k_d. Moreover, values of K_s simply reflect the efficiency with which degradation occurs, thus by increasing the influent COD and decreasing the MLSS concentration, the process removal efficiency will decrease and in turn, K_s will increase. Simulation of the effluent COD clearly indicates that as SRT values were increased, effluent COD concentrations were found to decrease till a value beyond which no significant changes in effluent COD were noticed. Moreover, effluent COD concentrations were found to decrease with the increase in MLSS values at all SRT values; however, decrease of the effluent COD concentration was found to become less significant as the MLSS value was increased. This can be attributed to the investigated organic loading rates (influent COD concentrations) that were not high enough to show significant differences in effluent COD concentrations at higher MLSS values. Results of the AnIMBR sensitivity to the biokinetic coefficients under investigation clearly indicated that the AnIMBR performance was found to be directly proportional to k_d and K_s and inversely proportional to μ_m. Moreover, the process performance was found to be more sensitive to K_s than μ_m and k_d, regardless of the MLSS value. Therefore, extra caution must be taken when K_s is used, since variations can result in substantial changes in the effluent COD values.

Acknowledgment

The authors would like to thank King Fahd University of Petroleum & Minerals (Dhahran, Saudi Arabia) for financial and technical assistance provided throughout the research period.

References

[1] M. Zamanzadeh, W.J. Parker, Y. Verastegui, J.D. Neufeld, Biokinetic and molecular studies of methanogens in phased anaerobic digestion systems, Bioresour. Technol. 149 (2013) 318–326.

[2] J. Kim, K. Cho, G. Han, C. Lee, S. Hwang, Effects of temperature and pH on the biokinetic properties of thiocyanate biodegradation under autotrophic conditions, Water Res. 47 (2013) 251–258.

[3] Sh Mardani, A. Mirbagheri, M.M. Amin, M. Ghasemian, Determination of biokinetic coefficients for activated sludge processes on municipal wastewater, Iran. J. Environ. Health Sci. Eng. 8 (2011) 25–34.

[4] A. Pala, Ö. Bölükbaş, Evaluation of kinetic parameters for biological CNP removal from a municipal wastewater through batch tests, Process Biochem. 40 (2005) 629–635.

[5] M.H. Al-Malack, Determination of biokinetic coefficients of an immersed membrane bioreactor, J. Membr. Sci. 271 (2006) 47–58.

[6] A. Naghizadeh, A.H. Mahvi, A.R. Mesdaghinia, M. Sarkhosh, Bio-kinetic parameters in municipal wastewater treatment with a submerged membrane reactor (SMBR), Proceedings of 12th National Congress of Environmental Health, Tehran, Iran, October, 2008.

[7] J. Kaewsuk, W. Thorasampan, M. Thanuttamavong, G.T. Seo, Kinetic development and evaluation of membrane sequencing batch reactor (MSBR) with mixed cultures photosynthetic bacteria for dairy wastewater treatment, J. Environ. Manage. 91 (2010) 1161–1168.

[8] S. Kantawanichkul, Application of Hollow Fiber Membrane Bioreactor to Anaerobic Treatment of Oily Wastewater by Photosynthetic Bacteria: Rhodobacter Sphaeroides, PhD Dissertation, Asian Institute of Technology, Bangkok, Thailand, 1990.

[9] I. Somiya, A. Kuriyama, I.H. Kamaish, Y. Ono, The development of anaerobic microbial reactor by purple nonsulfur bacteria for domestic wastewater treatment, Proceedings of the Second IAWPRC Asian Conference on Water Pollution Control, Bangkok, Thailand, November, 1988.

[10] N. Noparatnaraporn, Y. Nishisawa, M. Hayashi, S. Nagai, Single cell protein production from cassava starch by Rhodopseudomonas gelatinosa, J. Ferment. Technol. 61 (1981) 515–519.

[11] N. Noparatnaraporn, S. Trakulnaleumsai, R.G. Silveira, Y. Nishizawa, S. Nagai, SCP production by mixed culture of Rhodocyclus gelatinosus and Rhodobacter sphaeroides from Cassava waste, J. Ferment. Technol. 65 (1987) 11–16.

[12] F. Nakajima, N. Kamiko, K. Yamamoto, Organic wastewater treatment without greenhouse gas emission by photosynthetic bacteria, Water Sci. Technol. 35 (1997) 285–291.

[13] F. Carta-Escobar, J. Pereda-Marín, P. Álvarez-Mateos, F. Romero-Guzmán, M.M. Durán 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.

[14] S.H. Hwang, C.L. Hansen, Performance of upflow anaerobic sludge blanket (UASB) reactor treating whey permeate, Trans. ASAE 35 (1992) 1665–1671.

[15] Y. Yu, C.L. Hansen, S. Hwang, Biokinetics in acidogenesis of highly suspended organic wastewater by adenosine 5-triphosphate analysis, Biotechnol. Bioeng. 78 (2002) 147–156.

[16] W.C. Hu, K. Thayanithy, C.F. Forster, A kinetic study of the anaerobic digestion of ice-cream wastewater, Process Biochem. 37 (2002) 965–971.

[17] U. Wiesmann, I.S. Choi, E. Dombrowski, Fundamentals of Biological Wastewater Treatment, first ed., WILEY-VCH, Weinheim, Germany, 2007.

[18] C. Lin, Anaerobic digestion of pesticide-plant wastewater, Biol. Wastes 34 (1990) 215–226.

[19] G. Teissier, Growth of bacterial populations and the available substrate concentration, Rev. Sci. 3208 (1942) 209–214.

[20] D.E. Contois, Kinetics of bacterial growth: relationship between population density and specific growth rate of continuous cultures, J. Gen. Microbiol. 21 (1959) 40–50.

[21] M. Moser, in: G. Kibby (Ed.), Keys to Agarics and Boleti (Polyporales, Boletales, Agaricales, Russulales), Roger Phillips, London, 1978, pp. 118.

[22] J. Beltran, T. Gonzalez, J. Garcia, Kinetics of the biodegradation of green table olive wastewaters by aerobic and anaerobic treatments, J. Hazard. Mater. 154 (2008) 839–845.

[23] G. Tchobanoglous, F.L. Burton, H.D. Stensel, Wastewater Engineering: Treatment and Reuse, fourth ed., McGraw-Hill International, Boston, MA, 2014.

[24] A. Ahmad, R. Ghufran, Evaluation of the bio-kinetics of cement kiln dust in an upflow anaerobic sludge blanket reactor for treatment of palm oil mill effluent as a function of hydraulic retention time, Sep. Purif. Technol. 133 (2014) 129–137.

[25] M. Henze, C.P.L. Grady, W. Gujer, G.V.R. Maraias, T. Matsuo, Activated Sludge Model No. 1 (ASM1), Research Report Published by IAWPRC, London, UK, 1987.

[26] M.H. Al-Malack, G.R. Aldana, Performance of anaerobic immersed membrane bioreactor (AnIMBR) treating synthetic dairy wastewater, Desalin. Water Treat. doi: 10.1080/19443994.2015.1129514.

[27] E.W. Rice, R.B. Baird, A.D. Eaton, L.S. Clesceri (Eds.), Standard Methods for the Examination of Water and Wastewater, twenty-second ed., APHA, AWWA, WEF, Washington, DC, 2012.

[28] J. Kaewsuk, W. Thorasampan, M. Thanuttamavong, G.T. Seo, Kinetic development and evaluation of membrane sequencing batch reactor (MSBR) with mixed cultures photosynthetic bacteria for dairy wastewater treatment, J. Environ. Manage. 91 (2010) 1161–1168.

[29] M.D. LaGrega, P.L. Buckingham, J.C. Evans, Hazardous Waste Management, second ed., McGraw Hill, Boston, MA, 2001.