

Determinación de parámetros CINÉTICOS Y operacionales para el diseño de un reactor UASB a escala real

Determination of kinetic and operational parameters for full-scale uasb design

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Resumen

El objetivo de este trabajo fue determinar la constante de velocidad (K), los coeficientes de rendimiento celular (Y) y de decaimiento endógeno (k_e) y algunos parámetros operacionales para el diseño de un reactor UASB a escala real para el tratamiento de las aguas residuales municipales generadas en el campus de la Universidad Autónoma Metropolitana - Azcapotzalco. Para este fin, un reactor UASB a escala de laboratorio fue operado bajo cuatro TRH diferentes (4, 6, 8 y 12 h) durante seis meses. La remoción de la DQO total varió entre 50% al TRH de 4 horas hasta un 75% al TRH de 12 horas, se obtuvieron resultados similares con los parámetros de DBO_5 y SST. Una prueba t de Student apareada mostró que la remoción de DQO obtenida con los cuatro TRH estudiados fue significativamente diferente al TRH de 12 horas; por lo tanto, se recomienda este TRH para el diseño del reactor UASB a escala real. La constante de velocidad (K) a 21 °C fue $8 \times 10^{-5} \text{ L} / \text{mg SSV} - \text{d}$, basado en la soluble DBO_5 y $3 \times 10^{-5} \text{ L} / \text{mg SSV} - \text{d}$ basado en la DQO soluble, estos valores son considerados bajos, lo que indica la presencia de una cantidad importante de compuestos orgánicos de difícil degradación, probablemente procedentes de las aguas residuales generadas en los laboratorios universitarios. Los coeficientes cinéticos fueron $Y = 0.0427 \text{ mg SSV} / \text{mg } DBO_5$ y $k_e = 0.02 \text{ d}^{-1}$ basado en la DBO_5 soluble como sustrato y $Y = 0.0596 \text{ mg SSV} / \text{mg DQO}$ y $k_e = 0.04 \text{ d}^{-1}$ basado en la DQO soluble como sustrato. El tiempo medio de residencia celular (θ_c) en el reactor UASB a

escala de laboratorio fue de 49.5 días, aunque se recomienda un θ_c de 99 días para el diseño del reactor UASB a escala real.

Palabras clave: Agua residual municipal, Coeficientes cinéticos, degradación anaerobia.

Abstract

The aim of this study was to determine the rate constant (K) coefficients cell yield (Y) and endogenous decay (ke) and some operational parameters for the design of a UASB reactor-scale for water treatment residual municipal generated on the campus of the Universidad Autonoma Metropolitana - Azcapotzalco. To this end, a UASB reactor laboratory scale was operated under four different TRH (4, 6, 8 and 12 h) for six months. The removal of total COD ranged from 50% to HRT of 4 hours to 75% at HRT of 12 hours, similar results were obtained with the parameters of BOD5 and TSS. A Student's t test paired showed that the COD removal obtained with the four TRH studied was significantly different from HRT than 12 hours; therefore, it is recommended that TRH for design UASB-scale. The rate constant (K) at 21 ° C was 8×10^{-5} L / mg SSV - d, based on the BOD5 soluble and 3×10^{-5} L / mg SSV - d based on the soluble COD, these values are considered low, indicating the presence of a significant amount of organic compounds of difficult degradation, probably from the wastewater produced in university laboratories. The kinetic coefficients were $Y = 0.0427$ mg SSV / mg BOD5 and $ke = 0.02$ d-1 based on soluble BOD5 as substrate and $Y = 0.0596$ mg SSV / mg COD and $ke = 0.04$ d-1 based on the soluble COD as substrate. The average time of cell residence (θ_c) in the UASB reactor at laboratory scale was 49.5 days, although it recommends a θ_c of 99 days for the reactor design UASB-scale.

Key words: Anaerobic degradation, Kinetic coefficients, Municipal wastewater

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1. INTRODUCTION

The up-flow anaerobic sludge blanket (UASB) reactors have proven to be a viable and sustainable technology for the treatment of municipal wastewater in developing countries and small communities based on their low investment, operation and maintenance costs (Foresti *et al.*, 2006; Khan *et al.*, 2011). As a result, most of the full-scale municipal UASB reactors have been installed in India and Latin-America, and, by 2004 more than 50 installations had been reported (WEF *et al.*, 2010).

Conversely, design and operation of these facilities with municipal wastewater remains limited at regions with warmer temperature; and, consequently, limited design and performance data are available regarding UASB performance for treatment of municipal wastewater (WEF *et al.*, 2010).

On the other hand, historically, the stability and performance of anaerobic treatment systems have been considered poor in comparison to aerobic systems. However, with improved understanding of the factors that affect their performance, it has been possible to obtain a stable and reliable performance (Leslie Grady *et al.*, 2003). Hence, even with an increasing number of full-scale UASB installations, a thorough characterization of wastewater is essential and lab and pilot testing is desirable, before a new UASB be installed (Henze *et al.*, 2008).

Thus, the objective of this work was to determine the rate constant (K), the cell yield (Y) and the endogenous decay (k_e) coefficients and some operational parameters for the design of a full-scale UASB for the treatment of municipal wastewater generated at the Universidad Autónoma Metropolitana – Azcapotzalco campus through an experiment where a lab-scale UASB reactor was operated under four different hydraulic retention times (HRT).

2. MATERIALS AND METHODS

2.1 Experimental Set Up

A lab scale UASB reactor (6.1 L volume, PVC) was inoculated with sludge from a full-scale UASB reactor treating brewery wastewater. The municipal wastewater was obtained after primary sedimentation in the wetland system constructed at the Metropolitan Autonomous University - Azcapotzalco Campus and pumped to the UASB reactor using a peristaltic pump (Model Masterflex 7553-30, Cole-Parmer, USA). Temperature in the UASB reactor was maintained at 21 ± 1 °C during the experiment. The UASB reactor was operated until acclimated sludge was developed (approx. 2 months). The end of the acclimation period was determined by measuring the organic substrate concentration in the effluent; once this parameter reached the minimum value, the sludge in the reactor was considered acclimated. After acclimation was attained, the reactor was operated at steady state under four different

hydraulic retention times (HRT): 4, 6, 8 and 12 hours, during one month each HRT, and the information necessary to calculate the rate constant and the kinetics coefficients was obtained. During the experiment was not carry out any discharge of sludge, other than the volatile suspended solids (VSS) present in the effluent.

2.2 Analytical Methods

pH, temperature, dissolved oxygen (DO) and oxidation-reduction potential (ORP) were measured daily in the UASB reactor influent and effluent using an ion specific electrode (ISE) for each parameter (Model LabQuest, Vernier, USA). Total suspended solids (TSS), volatile suspended solids (VSS), total and soluble chemical oxygen demand (COD), biological oxygen demand (BOD₅) and alkalinity were measured twice per week according to the Standard Methods (1998). The ratio between partial and total alkalinity (PA/TA ratio) was calculated according to Soto *et al.* (1993).

2.3 Rate constant and kinetic coefficients determination

In the design of UASB reactors based on the Monod and Michaelis-Menten relationships, it is necessary to use equations that employ the following parameters:

- K = Rate constant considering a pseudo-first order reaction (mg COD or BOD / mg VSS - d)
- Y = Cell yield coefficient (mg VSS / mg COD or BOD removed)
- k_e = Endogenous decay coefficient (d⁻¹)
- μ = Growth coefficient (d⁻¹)
- μ_{max} = maximum value of the growth coefficient (d⁻¹)
- K_s = Substrate concentration with $\mu = \frac{1}{2} \mu_{max}$ (mg/L COD or BOD)

According to Reynolds & Richards (1996), it is not valid to assume a Y value and a k_e value and knowing other parameters, as substrate removal and biomass concentration, to calculate the reactor mean cell residence time (θ_c). For the usual case, the substrate concentration in the effluent is known, and μ_{max} , K_s , Y and k_e are determined from kinetic studies. Thus, the required θ_c can be determined using kinetic equations.

It is possible to obtain the reaction rate constant (K) and the cell yield (Y) and the endogenous decay (k_e) coefficients from one continuous-flow reactor operated at three or more food/microorganism (F/M) ratios during equal periods to conserve time (Reynolds & Richards, 1996).

The rate constant (K), is determined from eq. 2.1, which is based on the Monod equation, assuming that the substrate concentration is relatively small and a pseudo-first order reaction (Reynolds & Richards, 1996):

$$\frac{S_i - S_t}{X\theta_i} = K S_t \quad (2.1)$$

Where

- S_i = Influent substrate concentration (mg/L COD or BOD)
- S_t = Effluent substrate concentration (mg/L COD or BOD)
- X = Biomass concentration (mg/L VSS)
- θ_i = Hydraulic retention time (d)
- K = Rate constant (L/ mg COD or BOD - d)

Plotting the S_t values on x-axis and $\frac{S_i - S_t}{X\theta_i}$ on y-axis, will give a straight line if the biochemical reaction is pseudo-first order. The slope of this line is equal to the rate constant (K).

According to Reynolds & Richards (1996), the cell yield coefficient (Y) considers the portion of substrate converted to new cells; while the endogenous decay coefficient (k_e) accounts for the loss in cell mass due to oxidation of internal storage products for energy for cell maintenance, cell death and predation by organisms higher in the food chain, and, it appears to change with cell age. Kinetic coefficients can vary as a function of the wastewater source, the class of organic compounds degraded, the concentration of inert solids in wastewater, the COD converted to methane, the microbial population and temperature (WEF *et al.*, 2010).

The coefficients Y and k_e may be determined from one continuous-flow reactor operated under different HRT, using the relation that exists between substrate utilization and cell production, according to eq. 2.2 (Reynolds & Richards, 1996):

$$\frac{dX}{dt} = Y \frac{dS}{dt} - k_e X \quad (2.2)$$

Where

- dX/dt = rate of cell production (mg VSS / L-d)
- Y = Cell yield coefficient (mg VSS / mg COD or BOD removed)
- k_e = Endogenous decay coefficient (d^{-1})

- ds/dt = Rate of substrate utilization (mg COD or BOD / d)
- X = Biomass present inside biological reactor (mg VSS)

Dividing by X and using measurable increases during a determined period of time, eq. 2.2 gives eq. 2.3:

$$\frac{\Delta X / \Delta t}{X} = \frac{Y}{X} * \frac{\Delta S}{\Delta t} - k_e \quad (2.3)$$

Where

- ΔX = Change in the cell mass concentration (mg/L VSS)
- Δt = Time increment (d)
- X = Average cell concentration during the time increment (mg/L VSS)

The coefficients Y and k_e may be calculated by a modification of eq. 2.3, which is:

$$\frac{\Delta X / \Delta t}{X} = Y \left(\frac{S_i - S_t}{X \theta_i} \right) - k_e \quad (2.4)$$

Plotting the $\left(\frac{S_i - S_t}{X \theta_i} \right)$ values on x -axis and $\frac{\Delta X / \Delta t}{X}$ on y -axis, will give a straight line with the slope equal Y and y -axis intercept equal to k_e .

To determine the rate constant (K) and the coefficients Y and k_e in UASB reactor, were employed the values of soluble COD and BOD_5 from UASB reactor influent and effluent under the four different HRT studied.

2.4 Determination of the mean cell residence time in UASB reactor

According to Tchobanoglous *et al.* (2003), a mass balance on the inert material in the biological reactor yields:

$$\left[\begin{array}{c} \text{Accumulation of} \\ \text{inert material} \\ \text{in UASB reactor} \end{array} \right] = \left[\begin{array}{c} \text{Inflow of} \\ \text{inert material} \\ \text{in UASB reactor} \end{array} \right] - \left[\begin{array}{c} \text{Outflow of} \\ \text{inert material} \\ \text{in UASB reactor} \end{array} \right] + \left[\begin{array}{c} \text{Generation of} \\ \text{inert material} \\ \text{in UASB reactor} \end{array} \right]$$

This mass balance can be expressed as follows:

$$\frac{dX_i}{dt} = QX_{inf} + r_{X_i}V - \frac{VX_i}{\theta_c} \quad (2.5)$$

Where:

- X_i = Nonbiodegradable VSS in UASB reactor (mg/L VSS)
- X_{inf} = Nonbiodegradable VSS in influent (mg/L VSS)
- r_{xi} = Rate of nonbiodegradable VSS from cell debris (mg VSS / L - d)
- V = Volume of reactor (L)
- Q = Wastewater flowrate (L/d)
- θ_c = Mean cell residence time (d)

The rate of nonbiodegradable VSS (nbVSS) from cell debris (r_{xi}) is the eq. 2.6:

$$r_{X_i} = f_e k_e X V \quad (2.6)$$

Where

- f_e = Fraction of biomass that remains as cell debris (mg SSV / g SSV)

Combining eq. 2.6 and eq. 2.5 and considering that no exists accumulation of inert material inside UASB reactor, the eq. 2.7 is obtained:

$$0 = Q X_{inf} + f_e k_e X V - \frac{V X_i}{\theta_c} \quad (2.7)$$

If eq. 2.7 is solved for X_i :

$$X_i = \frac{X_{inf} \theta_c}{TRH} + f_e k_e X \theta_c \quad (2.8)$$

On the other hand, biomass concentration (X) may be calculated using eq. 2.9:

$$X = \frac{Y(S_i - S_1)}{(1 + k_e \theta_c)} * \frac{\theta_c}{TRH} \quad (2.9)$$

And combining eq. 2.8 and eq. 2.9, will give the solids production (X_T) as follows:

$$X_T = \frac{Y(S_i - S_1)}{(1 + k_e \theta_c)} + f_e k_e X V + X_{inf} \quad (2.10)$$

Where

- X_T = Net VSS production per day (mg/d VSS)

The first term of eq. 2.10 is related with solids production of heterotrophic biomass; meanwhile the second and third terms are related with cell debris and non biodegradable VSS in the influent, respectively.

Eq. 2.10 can be modified to calculate the solids production in terms of TSS, assuming a typical biomass VSS/TSS ratio of 0.85. This ratio may vary from 0.8 to 0.9.

$$X_{T,SST} = \frac{Y(S_i - S_1)}{(1 + k_e \theta_c) * 0.85} + \frac{f_e k_e X V}{0.85} + X_{inf} \quad (2.11)$$

Where

➤ $X_{T,SST}$ = TSS production per day (mg/d TSS)

Combining eq. 2.9 and eq. 2.11, yields eq. 2.12:

$$X_{T,SST} = \frac{Y(S_i - S_1)}{(1 + k_e \theta_c) * 0.85} + \frac{f_e k_e Y(S_i - S_1)}{(1 + k_e \theta_c) * 0.85} + X_{inf} \quad (2.12)$$

Eq. 2.12 was employed to calculate the mean cell residence time (θ_c) of the UASB reactor. In this equation was considered that TSS production per day ($X_{T,SST}$) was equal to TSS concentration in UASB reactor effluent, due to during the experiment was not carry out any discharge of sludge.

Then, eq. 2.12 was solved for θ_c using the coefficients Y and k_e , obtained according to the procedure explained in section 2.3, and the values of soluble COD and BOD₅ from UASB reactor influent and effluent. A θ_c value was obtained for each one of the four different HRT studied.

3. RESULTS AND DISCUSSION

3.1 UASB reactor performance

Table 1 shows the results obtained for the different parameters analyzed in the influent during the experiment, meanwhile Table 2 shows the results obtained in the UASB effluent.

Table 2 shows that pH values in UASB effluent followed the influent tendency. pH values in municipal wastewater were between 7.5 and 9, which are higher than those that usually occurs in municipal wastewater; this could be associated with the fact that sewage in the university campus also collects the wastewater generated in laboratories.

On the other hand, pH in UASB reactor was slightly basic (between 7.3 and 8.7) throughout the entire experiment, which is adequate for UASB reactor operation (van Haandel & Lettinga, 1994). According to Galli and McCarty

(1989), methanogenesis occurs with ORP values below than -170 mV, therefore the atmosphere inside the UASB reactor was suitable for methane production.

Total alkalinity values were higher during acclimation and 12 h HRT than in the period where the UASB reactor was operated under 6, 8 and 12 hours, following the tendency of UASB influent; however, this fact did not represent a sign of instability since the partial and total alkalinity ratio (PA/TA) was 0.95 ± 0.02 . According to Soto *et al.* (1993), the PA/TA ratio is a parameter that allows the monitoring VFA accumulation inside anaerobic reactors and it must be maintained near from 1 in order to prevent acidification.

Table 1.

Results for the different parameters analyzed at the UASB reactor influent

Parameter	Acclimation	HRT (hours)			
		12	8	6	4
pH	8.6±0.30	8.5±0.33	9.17±0.15	8.88±0.35	8.97±0.293
T (°C)	22±0.87	21.1±0.16	21.4±0.58	20.21±0.83	20.33±0.96
ORP (mV)	-239.6	-237.62±51.5	-224.8±20.71	-207.33±38.17	-227.61±49.52
DO (mg/L)	0.42±0.25	0.15±0.17	0.19±0.15	0.26±0.21	0.19±0.21
Alkalinity (mg/L CaCO ₃)	218.2±29.5	217.06±38.5	134.87±30.9	102.23±20.3	144.75±24.5
Total COD(mg/L)	640±195.6	639.53±200.66	366.26±112.32	268.55±73.8	407±123.7
Soluble COD(mg/L)	339±117.45	338.7±129.17	213.88±58.22	147.70±42.45	257.23±67.38
Soluble BODs (mg/L)	140.1±6.01	207±48.08	181.25±76.72	209.5±2.12	138±14.14
Total carbon (mg/L)	326.9±73.4	211.72±43.39	138.86±39.09	216.99±77.8	167.06±17.05
Organic carbon (mg/L)	180±63.2	58.9±43.25	19.85±9.7	59.37±54.40	24.70±16.15
TS (mg/L)	1066±168.2	1065.83±116.5	788.01±339.5	922.7±171.3	1084.01±38.15
TSS (mg/L)	696±43.2	695.1±288.43	573.34±255.5	740±113.4	806.67±31.06
VSS (mg/L)	371±165	370.6±231.35	214.6±85.4	182.67±70.01	277.34±14.04

Table 2.

Results for the different parameters analyzed at the UASB reactor effluent

Parameter	Acclimation	HRT (hours)			
		12	8	6	4
pH	8.4±0.18	8.034±0.16	8.38±0.25	8.20±0.11	8.40±0.22
T (°C)	21.3±0.19	21.72±0.17	21.53±0.51	21.84±0.99	21.05±0.78
ORP (mV)	-283.16±37.75	-262.26±47.75	-243.78±23.7	-236.98±27.07	-243.51±41.03
DO (mg/L)	0.173±0.12	0.173±0.16	0.0625±0.08	0.047±0.061	0.017±0.03
Alkalinity (mg/L CaCO ₃)	238.4±52.3	238.4±56.71	156.25±22.16	131.33±19.7	145.88±22.16
Total COD(mg/L)	239.5±76.2	230.46±95.96	144.92±50.92	117.67±37.2	115.22±34.01
Soluble COD(mg/L)	144.72±66.2	154.71±59.04	91.19±29.47	85.87±24.7	82.09±15.92
Soluble BOD ₅ (mg/L)	95.5±12.72	70.25±4.59	77.75±15.90	113.5±2.12	78±2.82
Total carbon (mg/L)	144.8±43.10	154.50±33.5	114.80±31.5	154.89±42.7	144.51±18.73
Organic carbon (mg/L)	12.72±26.76	23.53±16.02	5.91±5.08	20.58±16.52	5.79±4.31
TS (mg/L)	768.6±112.6	765.5±198.06	629.34±196.46	717.34±95.44	824±35.55
TSS (mg/L)	608±141.2	603.17±165.25	458.67±144.57	602.67±60.17	656±32
VSS (mg/L)	160±25.7	162.31±33.56	170.67±60.04	114.67±43.87	168±10.58

Total COD removal ranged from 50 % at 4 hours HRT to 75% at 12 hours HRT. Similar results were obtained with BOD and TSS. According to Giraldo *et al.* (2007), average removals of COD, BOD and TSS in UASB reactors installed in Latin America ranged from 56% - 79%, 45% - 81% and 45% - 81%, respectively. Thus, the results obtained in this study showed that UASB performance was acceptable and comparable to the reports in the literature. However, it is important to point out that a post treatment of UASB effluent is needed to meet secondary and advanced treatment standards. Current full-scale installations in developing countries strive low cost and simplicity and typically have only screening and grit removal for pretreatment, and wetlands or aerobic or facultative lagoons for posttreatment (WEF *et al.*, 2010).

A paired sample Student's t-test carried out with the COD removal obtained under the four HRT studied, revealed a significant difference with the results obtained at 12 hours HRT; hence, this HRT is recommended for the design of UASB at full-scale.

3.2 Determination of rate constant (K)

As mentioned in section 2.3, plotting the S_t values on x-axis and $\frac{S_i - S_t}{X \theta_i}$ on y-axis, will give a straight with a slope equal to the rate constant (K). A summary of the data employed to calculate K using the values of soluble BOD₅ is given in Table 3 and the linear fit of this data is depicted in figure 1. On the other hand, the data employed to calculate K using the values of soluble COD is given in Table 4 and plotted in figure 2.

Table 3.

Data from UASB reactor operated under four different HRT used to calculate K with soluble BOD₅ as substrate

HRT (d)	Si-St (mg/L soluble BOD ₅)	$\frac{S_i - S_t}{X\theta_t}$ (mg BOD ₅ /mg VSS-d)	St (mg/L soluble BOD ₅)
0.17	78	0.00789	103.5
0.25	94.5	0.00664	90.0
0.33	103.5	0.00570	77.7
0.50	136.75	0.00526	70.2

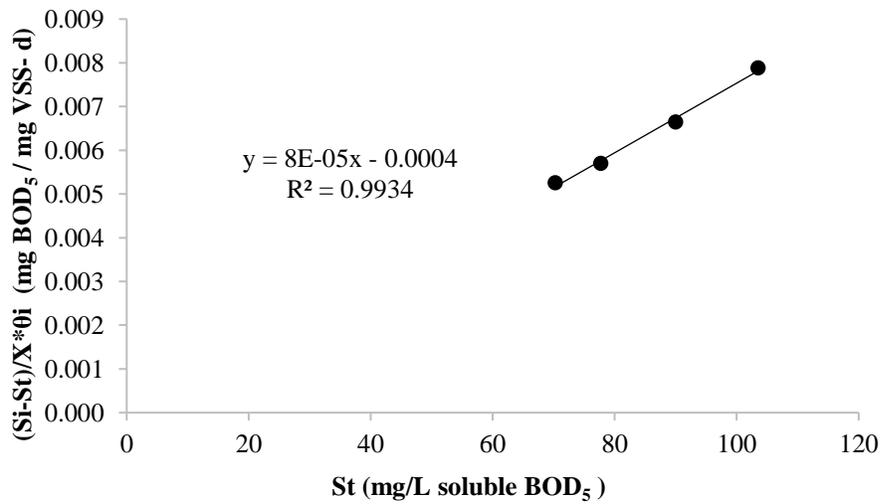


Figure 1. Linear fit for rate constant (K) calculation with soluble BOD₅ as substrate

Table 4.

Data from UASB reactor operated under four different HRT used to calculate K with soluble COD as substrate

HRT (d)	Si-St (mg/L soluble COD)	$\frac{S_i - S_t}{X\theta_t}$ (mg COD/mg VSS-d)	St (mg/L soluble COD)
0.17	91.8	0.00928	144.7
0.25	122.7	0.00862	105.2
0.33	155.1	0.00854	98.9
0.50	194.1	0.00746	82.1

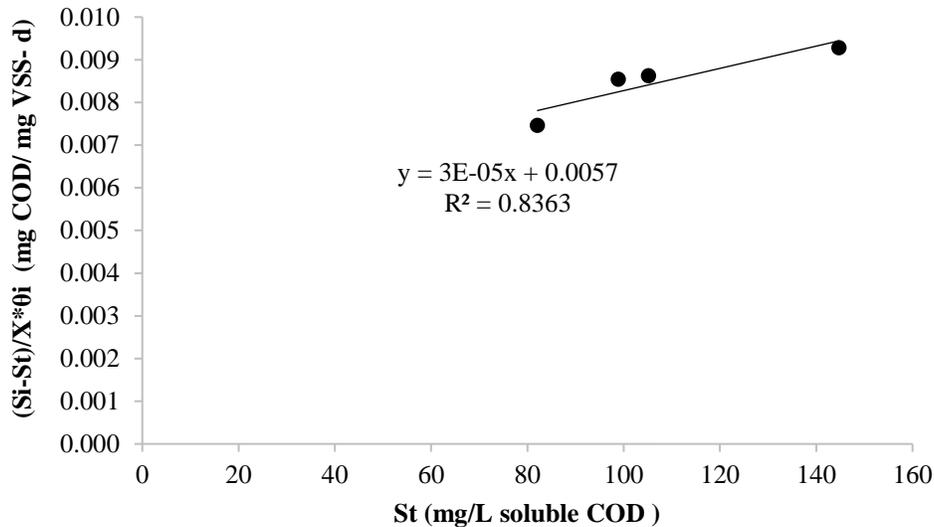


Figure 2. Linear fit for rate constant (K) calculation with soluble COD as substrate

Since in the municipal wastewater from this experiment there are numerous substrates present, the rate constant (K) represent an overall average value. As shown in figures 1 and 2, the rate constant (K) at 21 °C for the municipal wastewater from UAM-Azcapotzalco campus is 8×10^{-5} L/mg VSS – d based on soluble BOD₅ and 3×10^{-5} L/mg VSS – d based on soluble COD.

The value of the rate constant (K), depends primarily on the nature, complexity and composition of the wastewater, because the species of organic substrates will vary for different wastewaters (Reynolds & Richards, 1996). In particular, for municipal wastewaters containing significant amounts of chemical wastes, which is the case of the municipal wastewater from the campus of UAM-Azcapotzalco, as the sewage system collects the wastewaters from laboratories.

Besides, as only certain microbial species in an acclimated sludge can bio-oxidize a particular organic compound and because each species has its own particular rate of utilization, it follows that the overall rate constant (K) will vary for different types of wastewaters; even for municipal wastewaters, as the sewage systems could collect different organic compounds. In general, municipal wastewater has substrates more easily degraded than any of the industrial wastewater, although this is not always true. Thus, K values will be higher in municipal wastewaters than in the most industrial wastewaters.

Based on limited data, the rate constant (K), for municipal wastewaters ranges from 0.10 to 1.25 L/mg SS – h using total (soluble and insoluble) BOD₅ as a measure of organic content (Lin, 1989; Reynolds & Richards, 1996; Kalyuzhnyi & Davlyatshina, 1997; Pérez *et al.*, 1999; Montalvo & Guerrero, 2003). To compare the values

obtained in the present experiment with the values reported in scientific literature is difficult since temperature conditions were not the same and, also, the constants reported can be based on SS or VSS and different types of substrate (Total and soluble COD, BOD₅ and TOC). Nevertheless, the rate constant values found are low, which indicates that in the municipal wastewater studied exists a large quantity of organic compounds hardly degraded, probably coming from the wastewater generated in the university laboratories.

This fact emphasizes the importance of choosing a K value for UASB reactor design, since exists a wide range in K values; for this reason, is important to carry out experiments in order to obtain the rate constant (K).

3.3 Determination of kinetic coefficients (Y and k_e)

As mentioned in section 2.3, plotting the $\left(\frac{S_i - S_t}{X\theta_i}\right)$ values on x-axis and $\frac{\Delta X / \Delta t}{X}$ on y-axis, will give a straight line with the slope equal to the cell yield coefficient (Y) and y-axis intercept equal to the endogenous decay coefficient (k_e). A summary of the data employed to calculate Y and k_e using the values of soluble BOD₅ is given in Table 5 and the linear fit of this data is depicted in figure 3. The data employed to calculate Y and k_e using the values of soluble COD is given in Table 6 and plotted in figure 4.

The kinetic coefficients based on BOD₅ as substrate obtained were Y=0.0427 mg VSS/ mg BOD₅ and k_e=0.02 d⁻¹; and the kinetic coefficients based on COD as substrate were Y=0.0596 mg VSS/ mg COD and k_e=0.04 d⁻¹.

Because the energetics of anaerobic processes results in lower biomass production by a factor of 6 to 8 times compared with aerobic processes, consequently, the biomass yield and decay are lower.

Tchobanoglous *et al.* (2003) stated that for anaerobic digestion of municipal wastewater, the values of the cell yield coefficient (Y) reported in literature ranged from 0.05 to 0.10 mg VSS/ mg COD, with a typical value of 0.08 mg VSS/ mg COD, while Qasim (1999) reports values of the cell yield coefficient (Y) from 0.04 to 0.10 mg VSS/ mg BOD₅, with a typical value of 0.06 mg VSS/ mg BOD₅.

On the other hand, the values of the endogenous decay coefficient (k_e) ranged from 0.02 to 0.04 d⁻¹, with a typical value of 0.03 d⁻¹ (Tchobanoglous *et al.*, 2003). Therefore, the kinetic coefficients (Y and k_e) obtained in this experiment are in the interval reported in literature, although are bellow of those considered typical from municipal wastewater.

This result is in accordance with the values obtained for the rate constant (K), which showed that the municipal wastewater employed in this experiment had hardly degraded organic material; and, as the new cells generated are proportional to the portion of substrate degraded, with a substrate with hardly degraded material, the cell yield will

be lower. These lower values of the kinetic coefficients resulted in a less biological sludge production during the experiment (an increase of 5% after six months of operation, regarding initial biomass in UASB reactor), which in full-scale operation represents a decrease in handling and hauling costs, yielding savings of approximately 10% compared to aerobic process (Speece, 1996).

Table 5.

Data from UASB reactor operated under four different HRT used to calculate Y and k_e with soluble BOD_5 as substrate

HRT (d)	$S_i - S_t$ (mg/L soluble BOD_5)	S_t (mg/L soluble BOD_5)	$\frac{S_i - S_t}{X\theta_i}$ (mg BOD_5 /mg VSS - d)	$(\Delta X/\Delta t)/X$ (d ⁻¹)
0.17	78	103.5	0.00789	0.000137
0.25	94.5	90	0.00664	0.000103
0.33	103.5	77.75	0.00570	0.000049
0.50	136.75	70.25	0.00526	0.000026

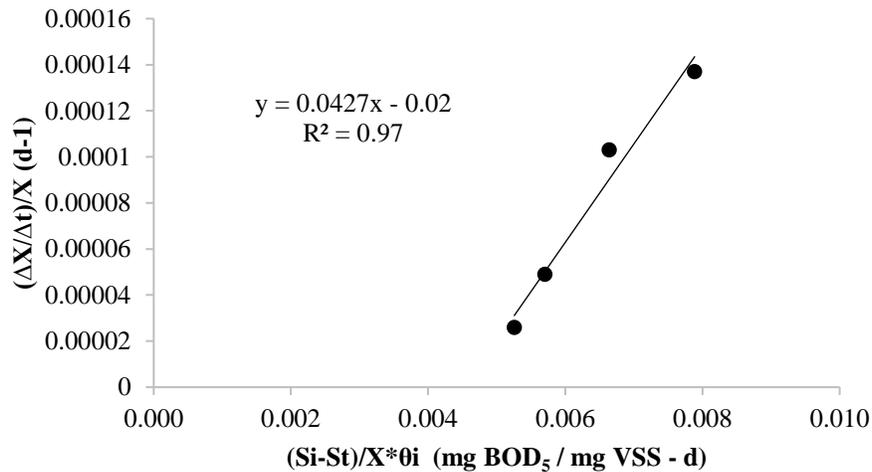


Figure 3. Linear fit for cell yield coefficient (Y) and endogenous decay coefficient (k_e) calculation with soluble BOD_5 as substrate

Table 6.

Data from UASB reactor operated under four different HRT used to calculate Y and k_e with soluble COD as substrate

HRT (d)	$S_i - S_t$ (mg/L soluble COD)	S_t (mg/L soluble COD)	$\frac{S_i - S_t}{X\theta_i}$ (mg COD/ mg VSS - d)	$(\Delta X/\Delta t)/X$ (d ⁻¹)
0.17	91.8	144.7	0.00928	0.000137
0.25	122.7	105.2	0.00862	0.000103
0.33	155.1	98.9	0.00854	0.000049
0.50	194.1	82.1	0.00746	0.000026

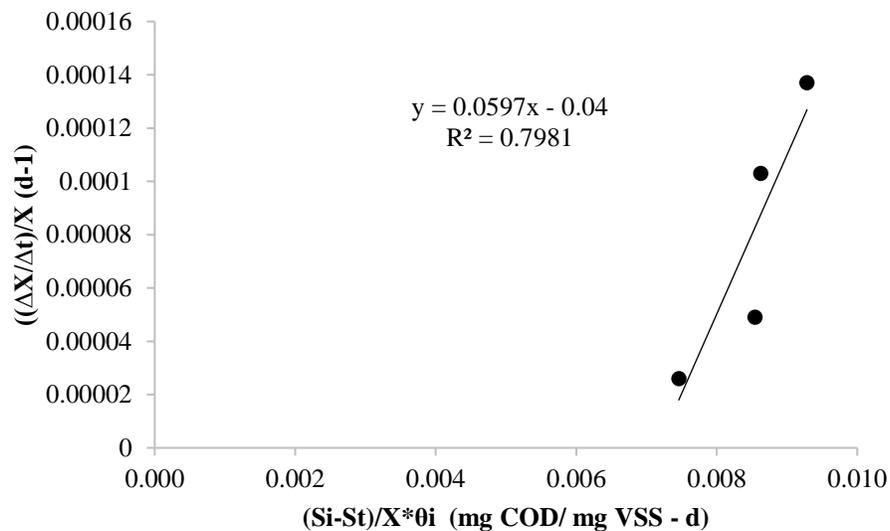


Figure 4. Linear fit for cell yield coefficient (Y) and endogenous decay coefficient (k_e) calculation with soluble COD as substrate

3.4 Determination of the mean cell residence time in UASB reactor

In order to determine θ_c of the UASB reactor, was employed the equation 2.12 presented in section 2.4. In this equation was considered that the TSS production per day ($X_{T, SST}$) was equal to TSS concentration in the UASB reactor effluent, due to during the experiment was not to carry out any discharge of sludge.

Equation 2.12 was solved for θ_c using the coefficients $Y = 0.0427$ mg VSS / mg BOD₅ and $k_e = 0.02$ d⁻¹, obtained in section 3.3 using BOD₅ as substrate. These coefficients were chosen since the linear fit had a higher linear correlation coefficient (R^2). Also, were employed the results of BOD₅ obtained in the UASB reactor influent and effluent during the experiment, finding a θ_c value for each HRT studied. The data employed and results of θ_c are shown in table 7.

Table 7.

Data from UASB reactor operated under four different HRT used to calculate the mean cell residence time (θ_c) using the kinetic constants obtained with soluble BOD₅ as substrate

HRT (d)	(Si - St) mg/L soluble BOD ₅	Effluent TSS (mg/L)	Nonbiodegradable TSS in effluent (mg/L)	θ_c (d)
0.17	78.0	824.00	164.8	49.0
0.25	94.5	717.33	143.5	49.7
0.33	103.5	629.33	125.9	49.6
0.50	136.7	765.50	153.2	49.6

Mean cell residence time in the UASB reactor at lab scale was 49.5 days. The cell residence time is a fundamental design and operating parameter for all anaerobic processes (van Haadel *et al.*, 2006).

In general, θ_c values greater than 20 days are needed for anaerobic processes at 30 °C for effective treatment performance, with much higher θ_c values at lower temperatures (Tchobanoglous *et al.*, 2003). However, the θ_c found in this experiment was short, if is considered the suggestion of Henze *et al.* (2008), who recommended a θ_c of approximately 95 days at 20 °C for domestic wastewater treatment. For this reason, when θ_c is determined using kinetic coefficients, is recommendable to use a safety factor of 1.5 in UASB reactor design, this fact will permit a very stable performance and a short restauration after a shut down for extended periods of time (up to several months) (Leslie Grady *et al.*, 1999). Thus, θ_c recommended for full-scale UASB design is 99 days.

4. CONCLUSION

The UASB reactor is a sustainable technology for the treatment of municipal wastewater generated at the Universidad Autónoma Metropolitana – Azcapotzalco campus, since adequate levels of COD, BOD₅ and TSS removal were achieved, ranged from 50 % at 4 hours HRT to 75% at 12 hours HRT. A paired sample Student's t-test carried out with the COD removal obtained under the four HRT studied, revealed a significant difference with the results obtained at 12 hours HRT; hence, this HRT is recommended for full-scale UASB design. The rate constant (K) at 21 °C was 8×10^{-5} L/mg VSS – d based on soluble BOD₅ and 3×10^{-5} L/mg VSS – d based on soluble COD, values considered low; which indicates the presence of a large quantity of organic compounds hardly degraded, probably coming from the wastewater generated in the university laboratories. The kinetic coefficients were $Y = 0.0427$ mg VSS/ mg BOD₅ and $k_e = 0.02$ d⁻¹ based on soluble BOD₅ as substrate and $Y = 0.0596$ mg VSS/ mg COD and $k_e = 0.04$ d⁻¹ based on soluble COD as substrate. Mean cell residence time (θ_c) in the UASB

reactor at lab scale was 49.5 days; although, θ_c recommended for full-scale UASB design is 99 days, this value will permit a very stable performance and a short restauration after a shut down for an extended period of time.

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